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AIRCRAFT GROUND FIRE SUPPRESSION AND RESCUE SYSTEMS. BASIC RELATIONSHIPS IN MILITARY FIRES, PHASE IV; HIGH SPEED DISSEMINATION OF DRY CHEMICAL FIRE SUPPRESSION AGENTS

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DOD Aircraft Ground Fire Suppression and Rescue Office

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AIRCRAFT GROUND FIRE SUPPRESSION AND RESCUE SYSTEMS

BASIC RELATIONSHIPS IN MILITARY FIRES, Phase IV; High Speed Dissemination of Dry Chemical Fire Suppression Agents

NAVAL SURFACE WEAPONS CENTER
WHITE OAK LABORATORY
SILVER SPRING, MARYLAND 20910

and

STANFORD RESEARCH INSTITUTE
MENLO PARK, CALIFORNIA 95025

MAY 1975

FINAL REPORT

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DOD AIRCRAFT GROUND FIRE SUPPRESSION & RESCUE OFFICE
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Julius Singer

JULIUS SINGER, Program Manager
Aircraft Ground Fire Suppression
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The feasibility and effects of applying dry chemical fire suppression agents at very high rates were explored with a series of cascade and pool type jet-fuel fires. **Monnex and purple K powders** were dispensed at conventional rates with hand held extinguishers and at high rates with a rocket motor type disseminator. Typical discharge conditions with the high speed disseminator are discharge time, one to two seconds; agent velocity at impact with the fire, 90 to 180 mph; and density of the agent cloud, about 5×10^{-4} lb ft^{-3}.

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Fire sizes were 80 and 160 ft^2 for the cascading fuels and 78 ft^2 for the pool.

The high speed disseminator was not effective against the pool fires even the burning area was reduced by one half, either with protruding rocks or AFFF foam. Flames were temporarily knocked down but reignition always occurred.

Some of the cascading fuel fires were successfully extinguished with the high speed disseminator but 3/4 of the fires reignited. The experimental variables; i.e. fire characteristics, powder application pattern, residence time, and concentration are discussed but the parameters responsible for success or failure could not be established for most of the tests.

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1.0 INTRODUCTION

1.1 Uncontrolled Kinematic Fuel Fires

Under control, three-dimenstional fuel fires take their place among the most useful tools of modern technology. The kitchen stove, the welder's torch, the boiler plant, jet engines, and gas turbines all have a well-regulated burner or torch flame in common. As long as the control valve continues to function, these fires are easy to ignite, regulate, and control, but when the valve is missing, this obedient servant can become an undisciplined monster. Classical examples of the missing valve are burning oil wells, wrecked tankers of all kinds, ships, rail, and truck, crashed aircraft, and ruptured fuel lines ranging in size from small hydraulic tubes to giant oil and gas pipes. Depending on the available quantity of fuel and the environment, such fires have burned from hours to weeks. In contrast to stationary pools, fires in these kinematic fuels can be very difficult to extinguish.

Within this considerable array of hostile fires, this report focuses on cascading fuel fires and a new technique for applying powdered extinguishing agents. The objective was to explore the feasibility of applying dry powders to the jet-fuel fires at very high application rates. In scope, this report describes the disseminator and a series of field tests in which the capabilities of the system and the effects of high application rates were evaluated.

1.2 Background Information

Although dry chemical agents are widely used in portable fire extinguishers there are a number of unresolved questions regarding the mechanism of extinguishment and the importance of various test parameters. Early studies established that suppression involved chemical reactions beyond any physical interactions occurring in the combustion zone; however, the precise nature of the reactions are undetermined and probably will remain so until more is known about the reactive species in the flames. Despite these uncertainties, considerable practical information is available, e.g., laboratory tests have established that chemical composition, particle size, and application rate all influence the effectiveness of these chemical agents. Since suppression apparently involves reactive species, most attention has been given to salts containing ions or radicals that are good scavengers, e.g., the alkali metals and halogens. Commercial agents such as $NaHCO_3$, $KHCO_3$, $NH_4H_2PO_4$, and HCl are not the most effective compounds, but they offer a good compromise between the cost, convenient physical properties, and efficiency.

Particle size is determined by a suitable compromise between the chemical requirements for small particles to maximize the interacting surface area, and physical requirements for large particles to achieve a suitable trajectory into the flame plume. One clever approach involves lumps of very fine powder held together with a bonding agent that disintegrates and increases the contract area when the lumps encounter the flames. Particle sizes typically range from 10 to 75 micrometers.[1] Information about the critical application concentration for extinguishment and the variation in this factor with fire size and application rate is not well-defined in the literature. Since the critical application density must depend on the concentration of reactive species in the combustion zone, an ideal yardstick for extinguishment would establish this relationship. Unfortunately, measurements are limited to the powder applied, not the agent that arrives in the fire, e.g., the parameters commonly reported are fire area, agent discharge rate, and extinguishment time. Usually no information about the agent cloud shape, size, and residence time in the fire is available to indicate the application efficiency. Since the density of reactive species integrated over the combustion zone should be proportional to the burning rate, the ratio of powder application rate to fuel consumption rate provides an averaged indication of the desired yardstick. This technique has been used in Reference 1 and Table 1.1 summarizes some of the results along with values computed from Reference 2. Reviews of dry chemical suppression tests contain information mostly about the requirements for extinguishing pool fires. For example, Reference 3 lists application densities for potassium bicarbonate ($KHCO_3$) used to extinguish a variety of fuels and pool fires sizes as ranging from .1 to .5 pounds/ft^2 of fire bed. Application rates are typically 1.5 to 2 pounds/sec for 100 ft^2 fires, 4 to 8 pounds/sec for 400 to 800 ft^2 fires, and 25 pounds/sec in 1200 ft^2 fires. Reference 3 also notes that "Tests of dry chemical agent on the smaller fire sizes indicate an increase in agent required per unit area with increasing fire size. On the larger fires, the trend indicates that increasing the discharge rate may increase the agent required." Such rate and area effects are difficult to reconcile with a simple collision reaction model and may well indicate efficiency of application rather than properties of the agent and the fire. In the large pool fires of interest to Aircraft Ground Fire Suppression and Rescue (AGFSRS), the specific burning rate is reasonably constant; therefore, the same amount of powder should be adequate to accommodate the reactive species stemming from each unit area of fuel. Since the height of the flames are proportional to the fire diameter, it is assumed that the agent would be applied over the same relative volume regardless of diameter.

TABLE 1.1

AGENT REQUIRED TO EXTINGUISH CASCADE FIRES

AGENT TYPE	FIRE SIZE FT^2	DISCHARGE TIME SEC	AGENT DISCHARGED LBS	DISCHARGE RATE LBS/SEC	BURNING RATE GAL/SEC	AGENT FUEL LBS/SEC	REF.
MONNEX	48	11.5	86.	7.47	.067	111.5	2
MONNEX	48	6.3	51.	8.1	.067	120.8	2
MONNEX	80	6.0	50.	8.33	.111	75.	2
MONNEX	80	9.1	64.	7.04	.111	63.5	2
MONNEX	96	17.3	113.	6.54	.133	49.1	2
MONNEX	112	8.6	53.	6.16	.156	39.5	2
MONNEX	112	9.2	58.5	6.36	.156	40.8	2
PKP	48	43.	148.	3.44	.067	51.3	2
PKP	48	16.1	84.5	5.24	.067	78.2	2
PKP	80	6.5	78.	12.	.111	108.	2
PKP	80	7.	82.	11.7	.111	105.5	2
PKP	96	12.3	93.	7.56	.133	56.9	2
PKP	96	25.5	154.	6.04	.133	45.4	2
MONNEX	80	1.25	17.25	13.8	.111	124.5	THIS WORK
PKP	80	1.97	20.	10.2	.111	91.6	THIS WORK

AGENT	COMPOSITION	SPECIFIC SURFACE	APPARENT DENSITY	REFERENCE
MONNEX	$K(UREA)CO_3$	5500-6600	.64	5
PKP	$KHCO_3$	4200-5200	.88	5

Application rate effects should reflect the influence of reaction times which are very short and residence times, i.e., the time for the powder to be carried away in the convective column or ambient winds. Since the dry chemical provides no residual protection, the agent should remain in the reaction volume until the flames are out. The minimum residence requirements should correspond to simultaneous application over the entire combustion zone. Under such conditions the NBS experiments on very small fires indicate that the minimum specific application rate for extinguishment did not increase with fire size, but the application densities were not given.[1]

Reference 4 states that the current trends in equipment development are directed toward high-capacity dispersing systems capable of discharging powder at rates of several tons per minute for periods in excess of 2 minutes. Before participating in the substantial effort required to develop such equipment, it appears desirable to know more about the reported area and rate effects and to separate operational performance from the fundamental behavior of the agent. This test program was designed to shed some light on the rate effects. A rocket-motor type disseminator was selected to obtain application rates an order of magnitude greater than the conventional compressed air systems provided. At the Stanford Research Institute (SRI), powders and aerosols have been rapidly deployed, both by explosive and rocket-motor techniques; however, the latter approach is more highly developed and has been successful in generating controlled clouds of various materials. Reference 5 discusses the relative merits of various energy sources suitable for the high-speed dissemination of fire extinguishing powder, i.e., explosives which are the fastest, propellant gas generators which can be reasonably fast and compressed gas cylinders which are the slowest.

Specific energy requirements increase with the dissemination rate and soon reach levels that command due respect and attention to safety precautions. The energy source selected in Reference 5 was a hybrid unit which employed a pyrotechnic and liquid CO_2, i.e., a Cardox blasting device, to expel Purple K powder from an attached reservoir. Expulsion times were about 20 milliseconds or about 4 times as fast as the SRI Rocket motors. Despite this speed advantage, the rocket disseminator was selected for the cascade study because of available equipment and a potential for better control of cloud formation and trajectory.

2.0 EXPERIMENTAL PROCEDURE

2.1 High Speed Disseminators

2.1.1 Slurry Ejector

Figure 2.1 shows a cross section of the supersonic disseminator as modified to dispense a slurry of Monnex powder in water.* The reusable unit consists of three sections, the nozzle and injector housing (1), the rocket-motor chamber (2), and the slurry reservoir (3), where the bracketed numbers refer to call-outs in the drawing. Heavy-duty, split-ring clamps (4) hold the assembly together. In operation, ignition commences with activation of an electrically fired squib in the ignitor assembly (5). Next, the main propellant grain (6) begins to burn and develops a substantial pressure in the motor chamber (2). Most of the combustion products exhaust through the two carbon nozzles (7), but sufficient gas passes through the thrust director holes (8) in the separator block (9), to apply pressure to the slurry drive piston (10). As the piston moves, the slurry is forced through the delivery tube (11) to the ejector housing where a distriubtion plate (12) divides the flow and feeds the agent into the two exhaust jets. For a given type and geometry of propellant grain (6), the burning rate is controlled by the chamber pressure, which in turn is regulated by the nozzle throat area. Figure 2.2 shows the burning rate dependence on pressure for PBAN-175 observed in previous work. Appendix 5.1 contains the recipes for the PBAN-175 propellant grains and also for the Mag-Teflon ignitors. Appendix 5.2 describes the preparation of the slurries and the calculations and experimental measurements involved in designing the nozzles and the ejector ports for the slurry disseminator. For a design burning rate of 1.5 in. sec^{-1} the total nozzle area becomes 0.614 $in.^2$ or .307 $in.^2$ for each throat. Section 3.2.5 compares the advantages of Powder vs slurry dissemination.

2.1.2 Powder Ejector

The basic arrangement for disseminating powder is the same as for the slurry except for the method of ejecting the agent from the reservoir. Figure 2.3 shows the system modified to accommodate powder. Structurally, the piston has been removed and three flow tubes have been inserted in the separator block. Now the combustion products entering

*Monnex is a trademark of Imperial Chemical Industries, Ltd., England for Carbamic Powder, a dry chemical fire suppressant formulated from a reaction product of potassium bicarbonate and urea.

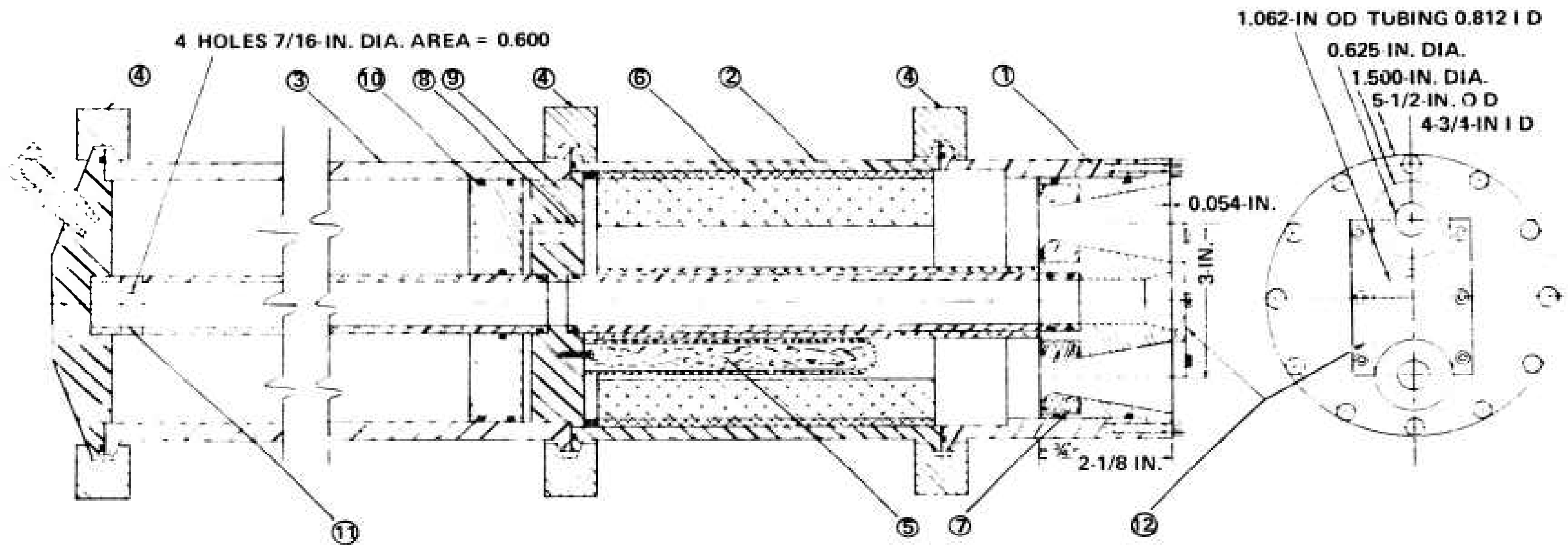


FIG. 2.1 CROSS SECTION OF SLURRY DISSEMINATOR ASSEMBLY

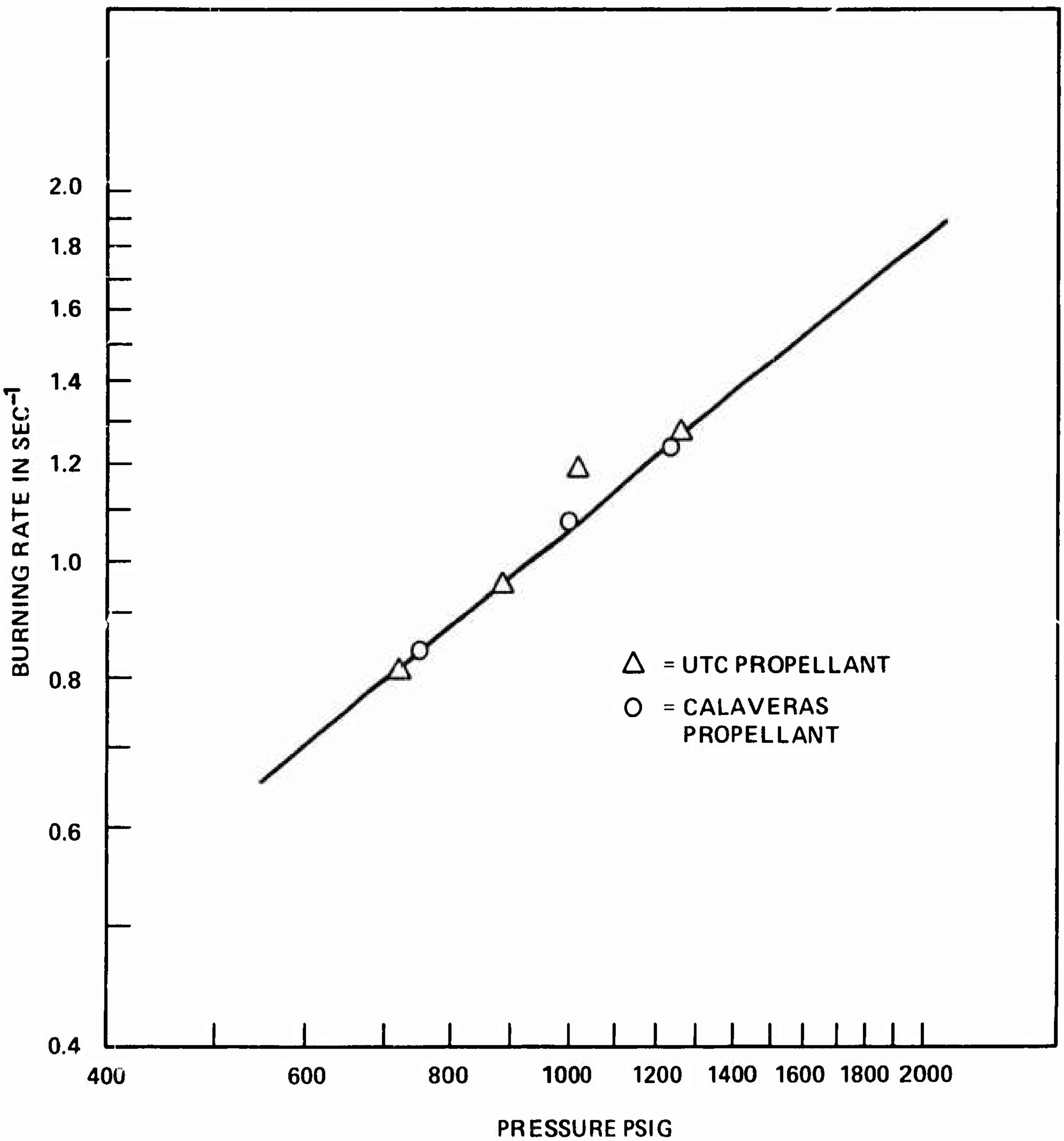


FIG. 2.2 PBAN-175 BURNING RATE AS A FUNCTION OF PRESSURE

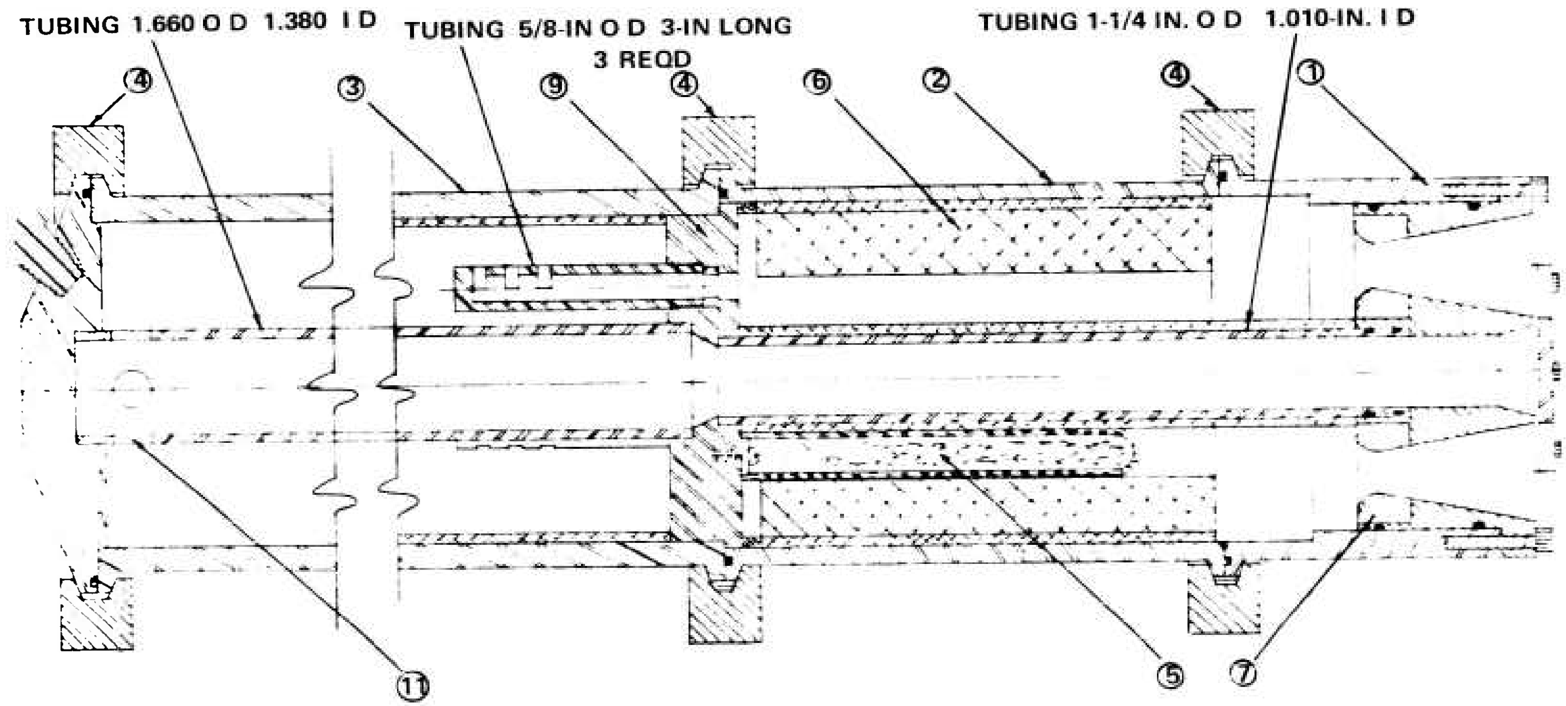


FIG. 2.3 CROSS SECTION OF POWDER DISSEMINATOR ASSEMBLY

the reservoir fluidize the powder and drive it out through the delivery tube. In the initial calculations, the combustion gases were allotted one-third to fluidize and eject the powder and two-thirds for flow through the nozzles. Appendix 5.3 contains the design calculations for these nozzle areas. Experience with the first few powder discharges indicated the need for less resistance to powder flow, i.e., only about one-half the agent was being discharged; therefore, the delivery tubes were expanded to the maximum diameter permitted by the nozzle block. The final dimensions are given in Figure 2.3.

Since the combustion products are hot enough to damage metal components, carbon inserts and phenolic sleeves are strategically located to provide thermal shielding. Fully loaded the chamber held 19 pounds of Monnex or 24 pounds or PKP.

2.1.3 Disseminator Mounts

Three factors determine the arrangement for mounting the disseminator; (1) Rocket thrust, (2) horizontal mobility, and (3) vertical angle of attack. As indicated in section 1.2, all high-speed discharge techniques involve considerable power. In the disseminator, the 1200 psi working pressure would generate over 700 pounds thrust from the nozzles; therefore, a stable platform was required. Since the thrust provided additional diagnostic information, one mount was arranged to permit thrust measurements as shown in Figure 2.4. Transverse motion either horizontally or verticaly was prohibited by the metal framework clamped to the forks of a Hyster. Axial motion is constrained by a load-cell that measures the rocket-motor thrust. This assembly was used during the Phase I and II tests on the 10 ft fires at Camp Parks. Besides providing a massive stable platform, the vertical and the tilt motion available on the Hyster fork, simplified aiming the discharge at the seat of the fire. Powder was applied both along horizontal and decending trajectories. Figure 2.5 shows the Hyster in the 15 ft elevated position with the disseminator mounted at an angle for a downward trajectory. Guide chains were used to brace the forklift in the fully extended position; however, judging by the kick observed during discharge, this precaution probably was unnecessary.

For the tests involving two disseminators fired simultaneously, one or both of the units were mounted on I-beam strongbacks as shown in Figure 2.5 and 2.12. One mount was positioned on an 8 x 20 ft flatbed trailer and the other in the bed of a dump truck; consequently, both units were readily moved for aiming purposes. Although these platforms were not as stable as the Hyster, quite satisfactory powder trajectories were achieved.

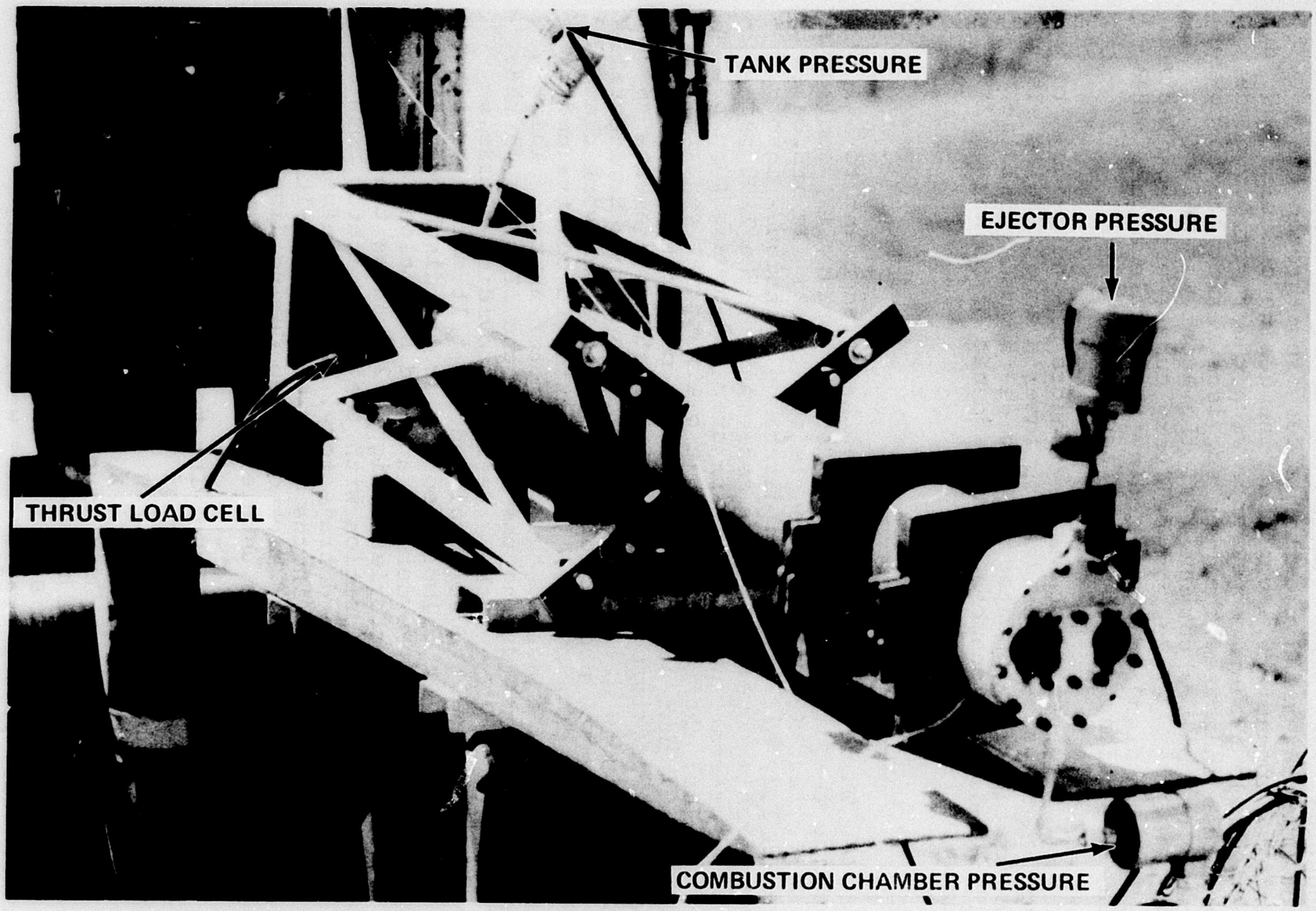


FIG. 2.4 DISSEMINATOR MOUNTED ON FORKS OF HYSTER READY TO DISCHARGE IN HORIZONTAL POSITION

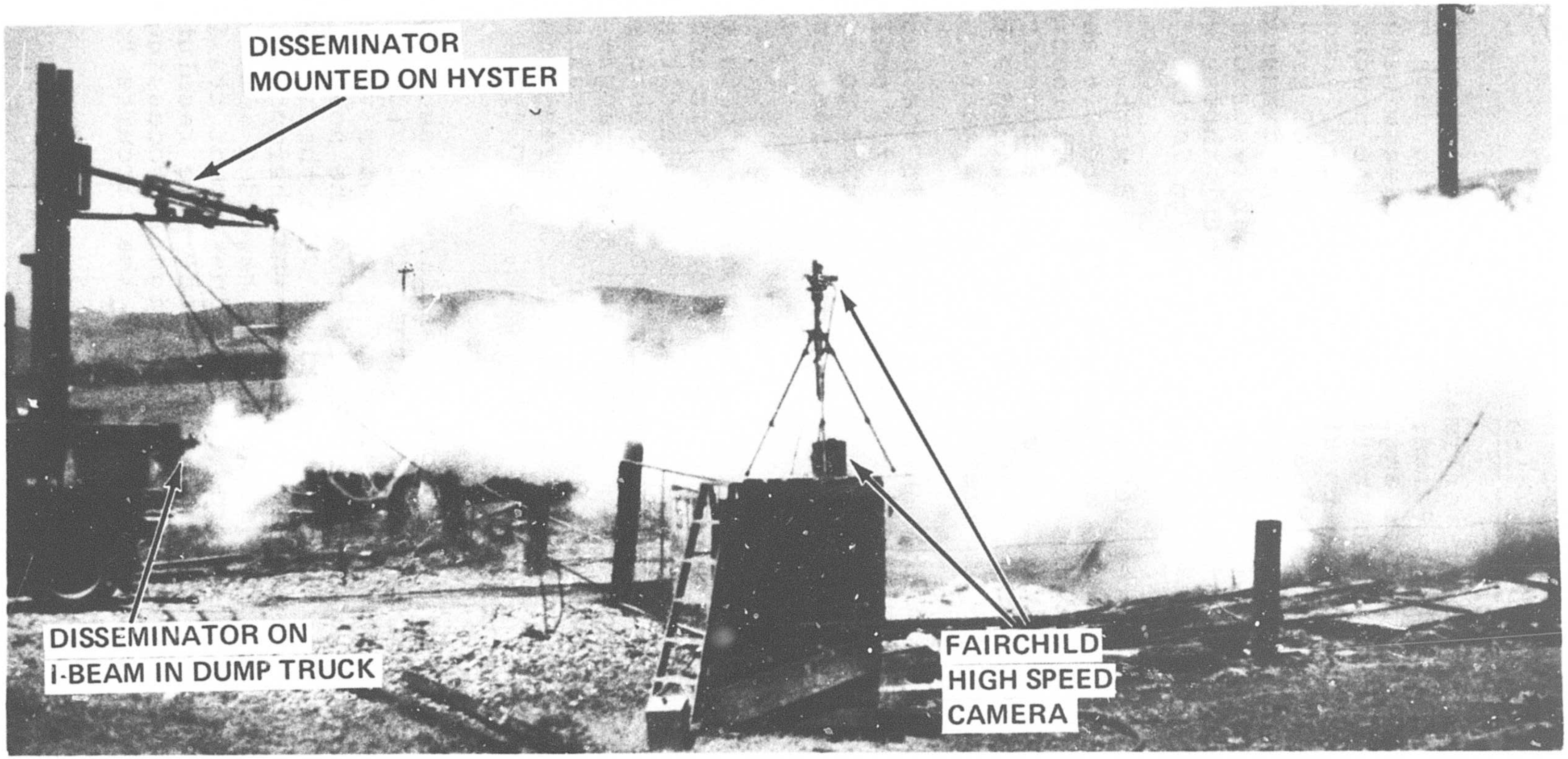


FIG. 2.5 TWO DISSEMINATORS DISCHARGED SIMULTANEOUSLY, ONE FROM THE I-BEAM MOUNT IN THE TRUCK AND THE OTHER FROM THE ELEVATED POSITION ON THE HYSTER. (TEST 25)

2.2 Instrumentation

2.2.1 Camp Parks Test Site

Three types of information were collected during the 10 ft fires at Camp Parks; (1) diagnostic data on the performance of the rocket engine and the disseminator, (2) characteristics of the test fire, and (3) the powder application pattern and its effect on the fire. Rocket-motor performance was evaluated on the basis of pressure readings in the three principal parts of the disseminator, i.e., the rocket-motor chamber, the powder reservoir, the the injection port. In addition, the total thrust was measured with the load-cell as mentioned in Section 2.1.3.

Fire characteristics were measured with radiometers, manometers, and cameras. Figure 2.6 shows the test arrangement and locations for the various instruments and pieces of equipment. The two rows of radiometers viewed the flames from positions 90^{o} apart and provided a temporal record of the radiation field throughout the test.

The electrical manometer mounted in the base of the fuel pan recorded changes in the fuel level for pool fires. With spray fires, the burning rate was assumed to equal the fuel discharge rate, i.e., .66 gallons/ft of fuel spray pipe.

The array of cameras monitored both the fire characteristics and the suppression effort. Two and sometimes three Super 8 Leicina cameras recorded the flame geometry and powder trajectory from two or three directions. A Fairchild 16 mm camera equipped with a wide-angle lens and running at 200 frames per second recorded in detail the development of the powder cloud and the suppression effects on the fire. A 16 mm Bolex and several 35 mm still cameras completed the documentation.

The row of thermocouples and the pressure gauge between the powder dispenser and the fire provided, respectively, another indication of the powder velocity and the force of the rocket blast 20 ft from the nozzle. Velocities were calculated from times when the powder cloud changed the temperature indicated by the thermocouples T_1 and T_2. All electrical signals were recorded simultaneously on a multichannel visacorder in the instrument trailer. With a paper speed of 2-1/2 in/sec, the time resolution was about .01 sec. In addition to the signal processing equipment the trailer also contained the circuits for arming and firing the disseminator motors.

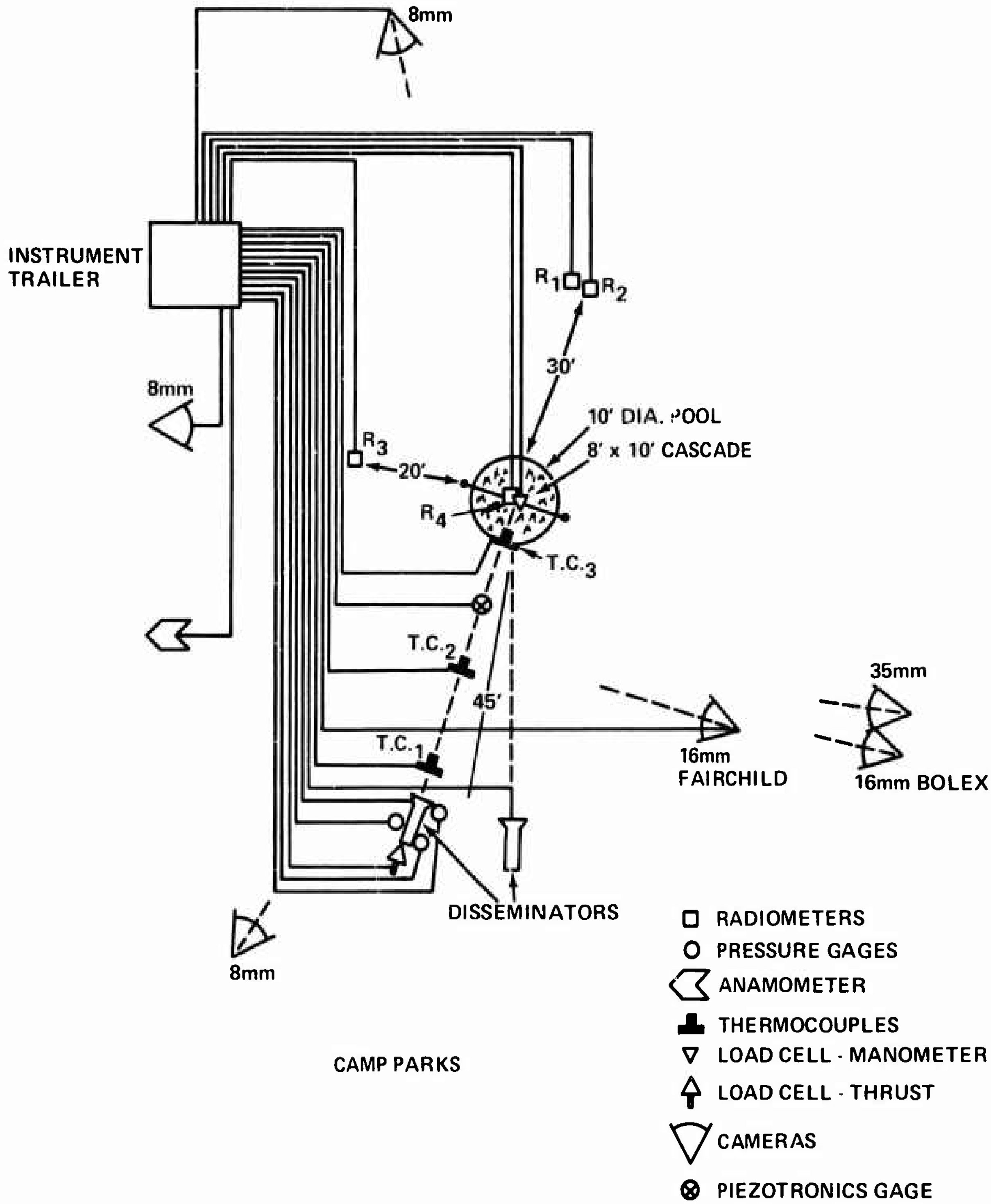


FIG. 2.6 INSTRUMENT LAYOUT FOR 10 FT POOL AND CASCADE FIRES AT CAMP PARKS.

2.2.2 LLL Site 300

During the Phase III tests at Site 300, instrumentation was limited to pressure readings in the motor chamber and photographic coverage. By this time, all of the disseminator dimensions had been established and the single pressure reading was considered an adequate indication of reproducibility. Figure 2.7 shows the locations of the cameras. As in the previous tests, the Fairchild camera recorded the broad-side view of the powder cloud at 200 frames/sec. Cloud volumes and velocities were obtained from these pictures. The 16 mm Bolex on its hilltop location provided a good aerial view of both disseminators and the entire fire test ground.

2.3 Test Fires

2.3.1 At Camp Parks

Three types of test fires were employed at Camp Parks, (1) pool, (2) cascade, and (3) pool plus cascade. Figure 2.8 shows a typical 10 ft diameter JP-4 pool fire in progress on a water substrate. Burning rates were about 5 mm/min which corresponds to 9.8 gpm for the total fuel area of 78.5 ft^2. Since these pool fires exceeded the extinguishing capacity of either the hand-portable extinguisher or the high-speed disseminators, the fire size was reduced either in area or burning rate for some of the tests. For area reduction without altering the specific burning rate, a dam was placed across the middle of the pan and half of the fuel surface was covered with AFFF just prior to ignition. Specific burning rates were reduced with a rock substrate by performing the suppression while the fuel surface area was reduced by protruding rocks.

Figures 2.9.1 and 2.10 show two somewhat different cascade fires burning over a water filled pan. The screen and fuel dispensing system were constructed according to the details outlined in Reference 2, namely, an 8 ft high, 10 ft long expanded metal screen, supported in an angle-iron frame. JP-4 was dispensed from a pipe along the top through 0.040 in. diameter holes spaced 1 in. apart. The total discharge rate for the 10 ft length was set at 6.6 gpm. Several characteristics of these fires deserve comment. Under the wind conditions of Figure 2.9.1, the flames do not extend along the expanded metal all the way to the ground. Ambient winds caused the flames to stand away from the screen downwind from the arriving cloud of powder. Second, all of the fuel is not consumed in the air, some falls to the ground and is burning beyond the 10 ft pan rim. AFFF had been applied in the pan to minimize combustion on the ground, but some of the foam has been destroyed. Finally,

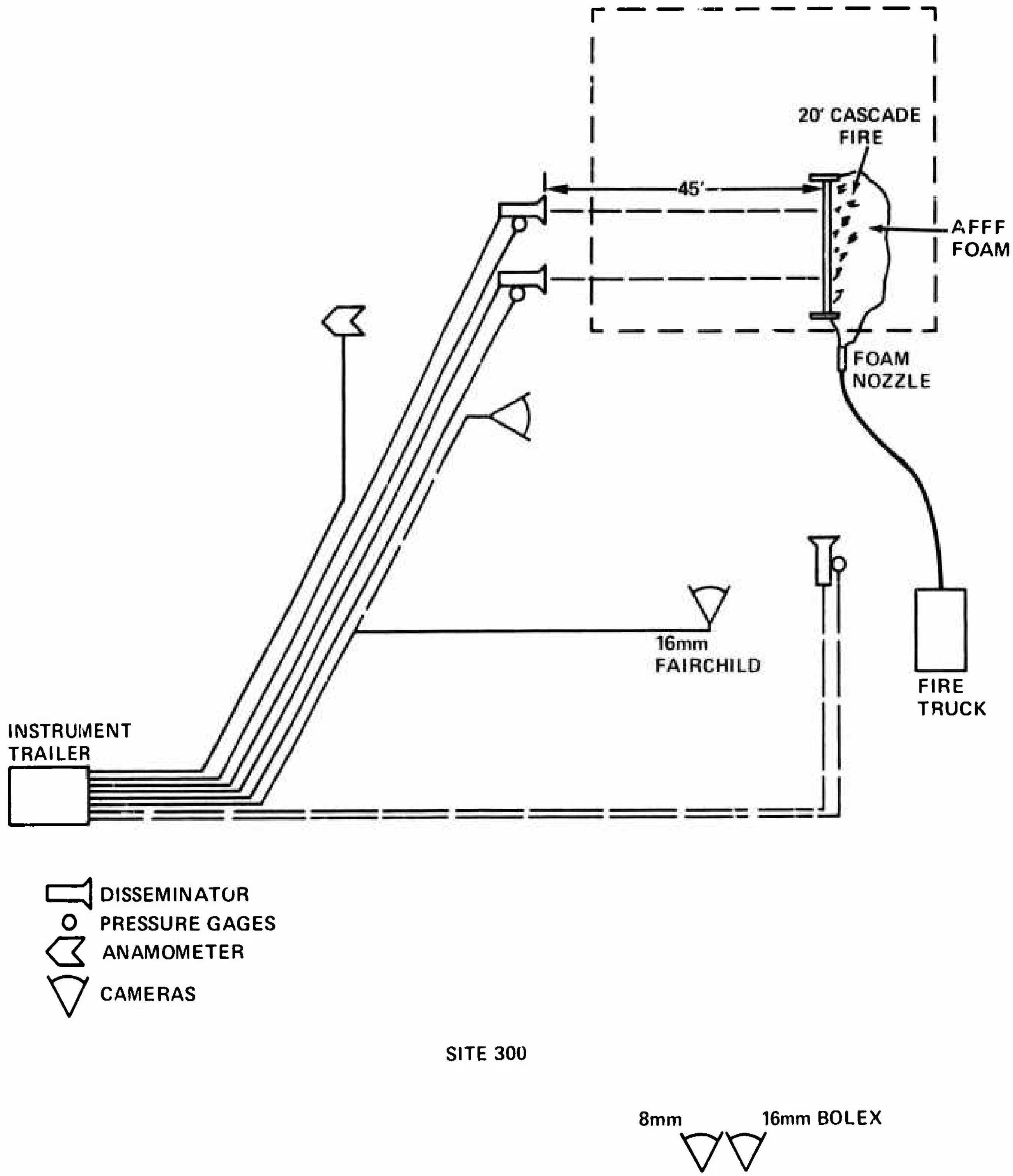


FIG. 2.7 INSTRUMENT LAYOUT FOR 20 FT CASCADE FIRES AT SITE 300.

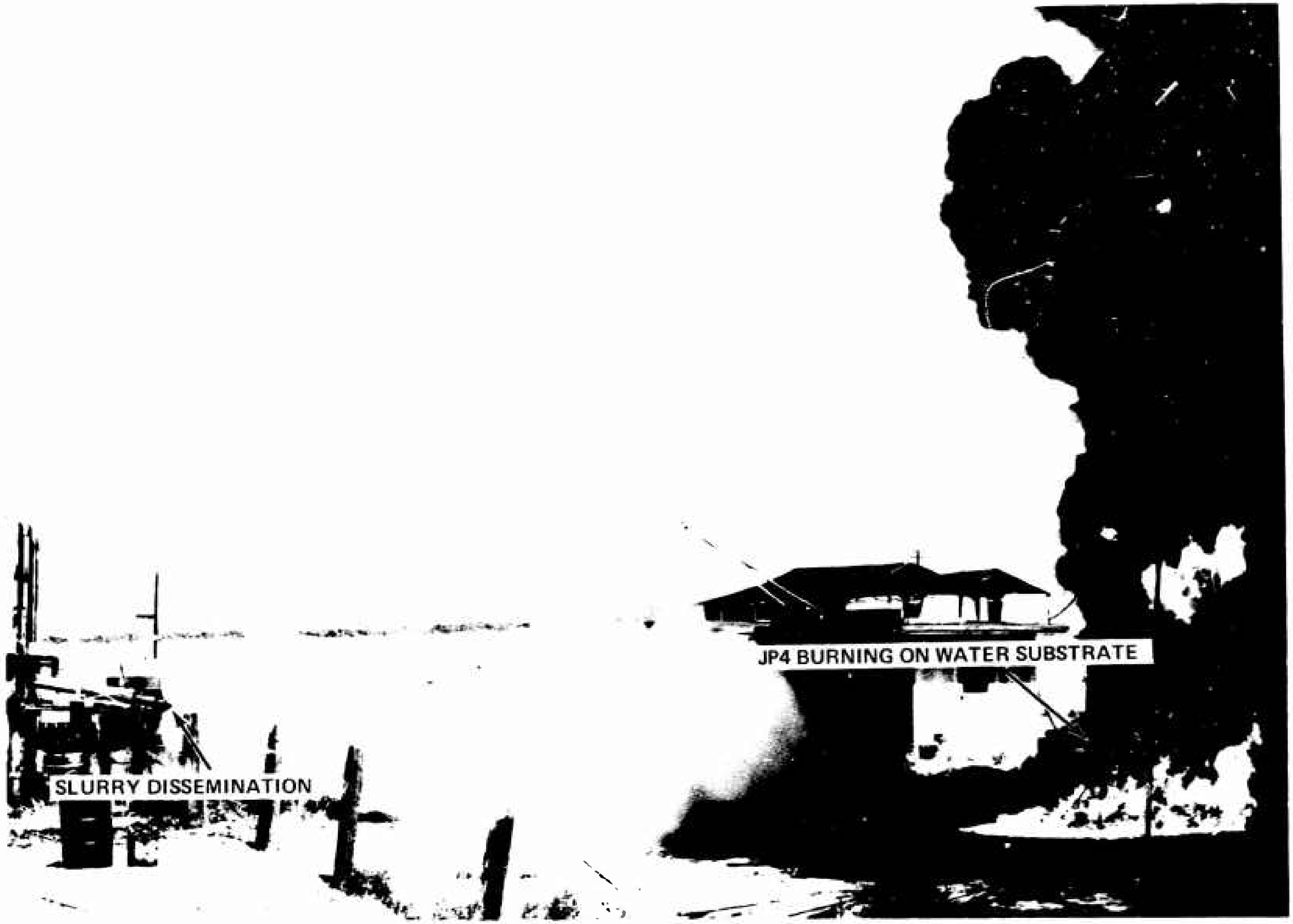


FIG. 2.8 TEN FOOT DIAMETER JP-4 POOL FIRE, EARLY STAGE OF DISCHARGE (TEST 1)

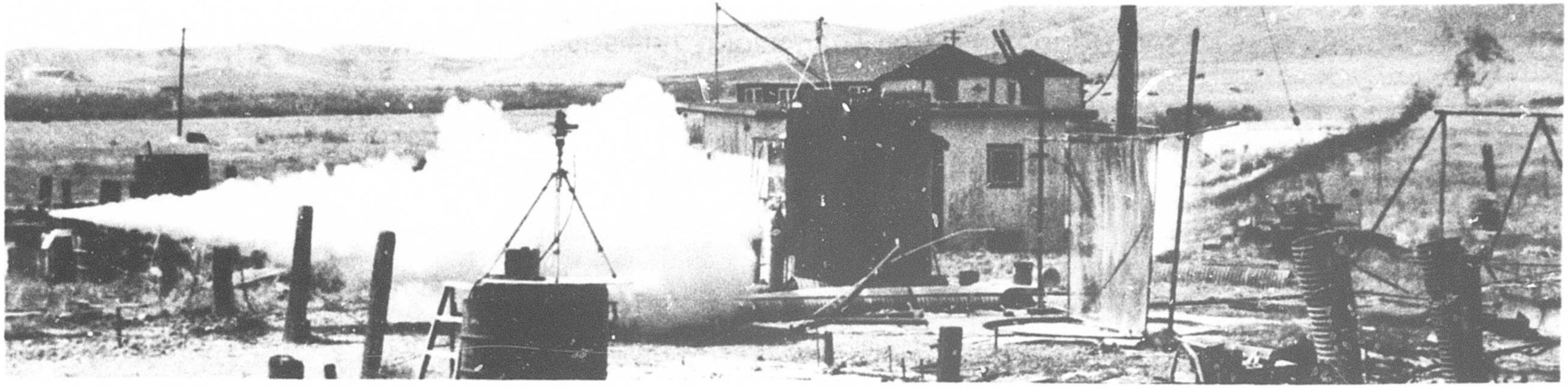


FIG. 2.9.1 TEN FOOT CASCADE FIRE UNDER WINDY CONDITIONS, EARLY STAGE OF DISCHARGE (TEST 9)

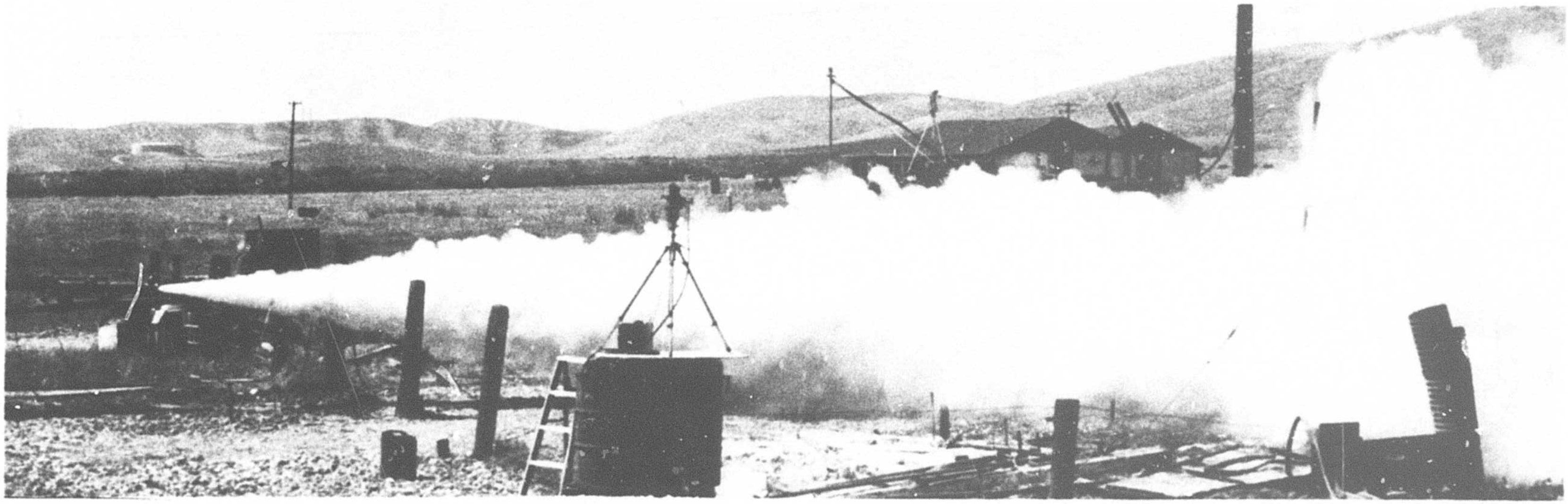


FIG. 2.9.2 CLOUD OF AGENT ENVELOPS THE CASCADE FIRE (TEST 9)

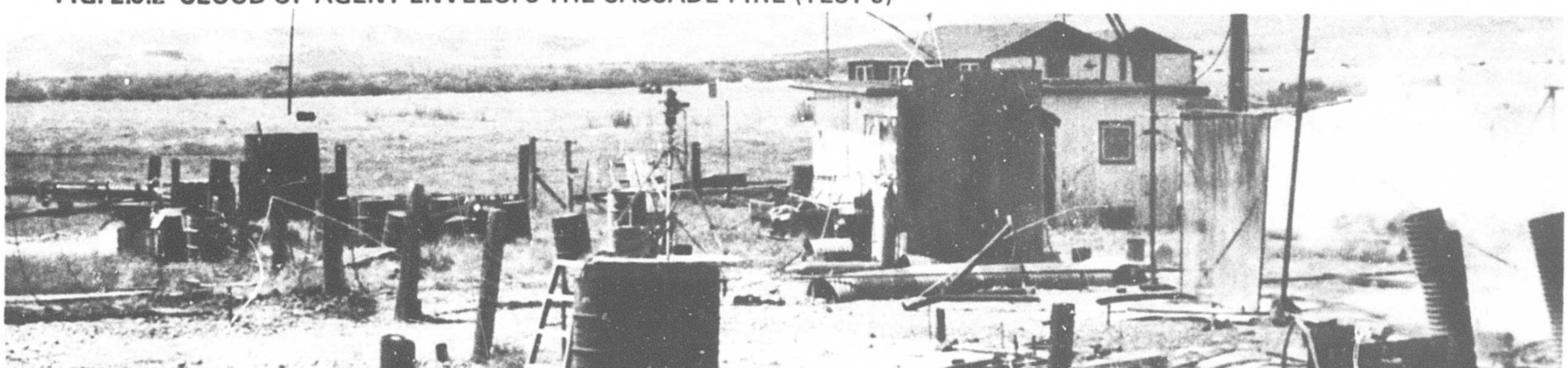


FIG. 2.9.3 CLOUD PASSES AND CASCADE FIRE IS EXTINGUISHED

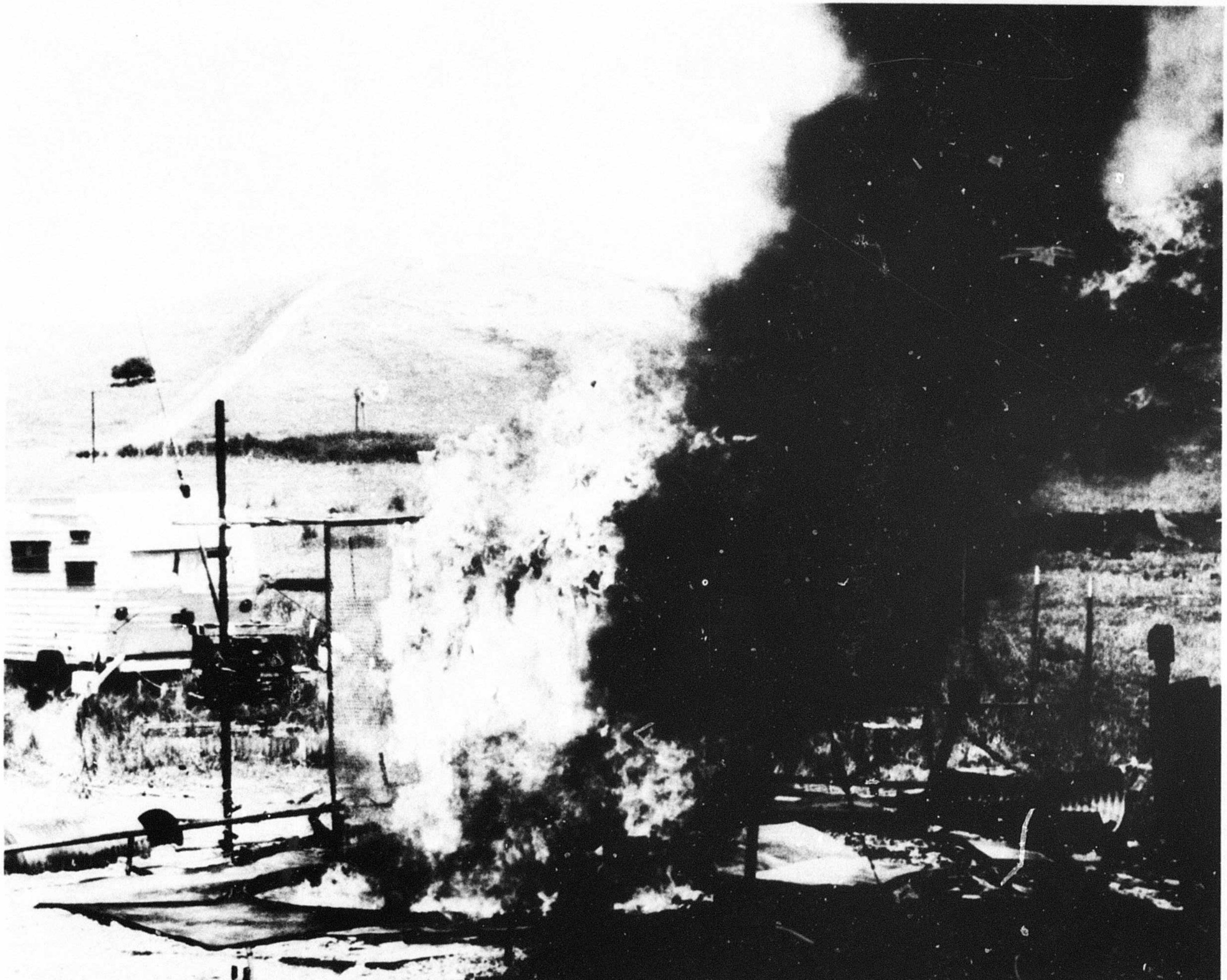


FIG. 2.10 TEN FOOT CASCADE FIRE UNDER VERY LOW WIND CONDITIONS (TEST 3)

there is virtually no smoke, indicating fairly complete combustion and the flames are a brighter yellow than observed in pool fire flames or in cascade fires with no wind as in Figure 2.10. This hotter fire is due to a better mixing of the fuel and air. The fire shown in Figure 2.10 correspond to quiet wind conditions. The flames extend all the way to the bottom of the screen and out into the pan. Besides exhibiting red flames, copious quantities of black smoke are produced, indicating relatively incomplete combustion.

Figure 2.11 shows a combination cascade plus pool fire. In all ways, the pool fire dominated the combination and it presented the principal extinquishment problem. Since the high-speed disseminator never successfully extinguished the pool fires, testing with the combination fire was limited to two initial attempts. The combined fuel consumption rate was about 16.4 gpm of which almost two-thirds comes from the pool.

In all cases at least a 30-sec preburn period followed full involvement of the fuel before the countdown for firing the disseminator commenced. This countdown lasted 10 sec which combined with an unmeasured lag between verbal authorization and the onset of countdown allowed from 40 to 60 sec of burning before suppression.

2.3.2 Site 300 Fires

Only cascade fires were employed in the tests at Site 300. A second 8 ft x 10 ft cascade screen and fuel supply pipe was combined with the unit employed at Camp Parks to provide a maximum test fire 20 ft long. Separate fuel lines fed the two spray pipes so that the units could be used either individually or in combination. Figure 2.12 shows a typical 20 ft fire in progress. The rock substrate is filled with water to a level approximately 1 in. below the top of the rocks. Again, all of the fuel did not burn before it reached the ground; consequently, AFFF was applied on the donwwind side of the screen to minimize the ground fire. Safety considerations dictated that all personnel stand well away from the line of fire during the powder dissemination; therefore, several rituals were employed to provide ground fire suppression with the foam. Initially, foam was applied before ignition or during the preburn period, but in these cases, the falling fuel always destroyed some of the foam and established a ground fire before the powder arrived. In the final tests, the foam nozzle was positioned and operated unmanned throughout both preburn and suppression periods. In most of the tests, the powder was applied broadside to the upwind side of the fire. Application parallel to the fire screen was attempted

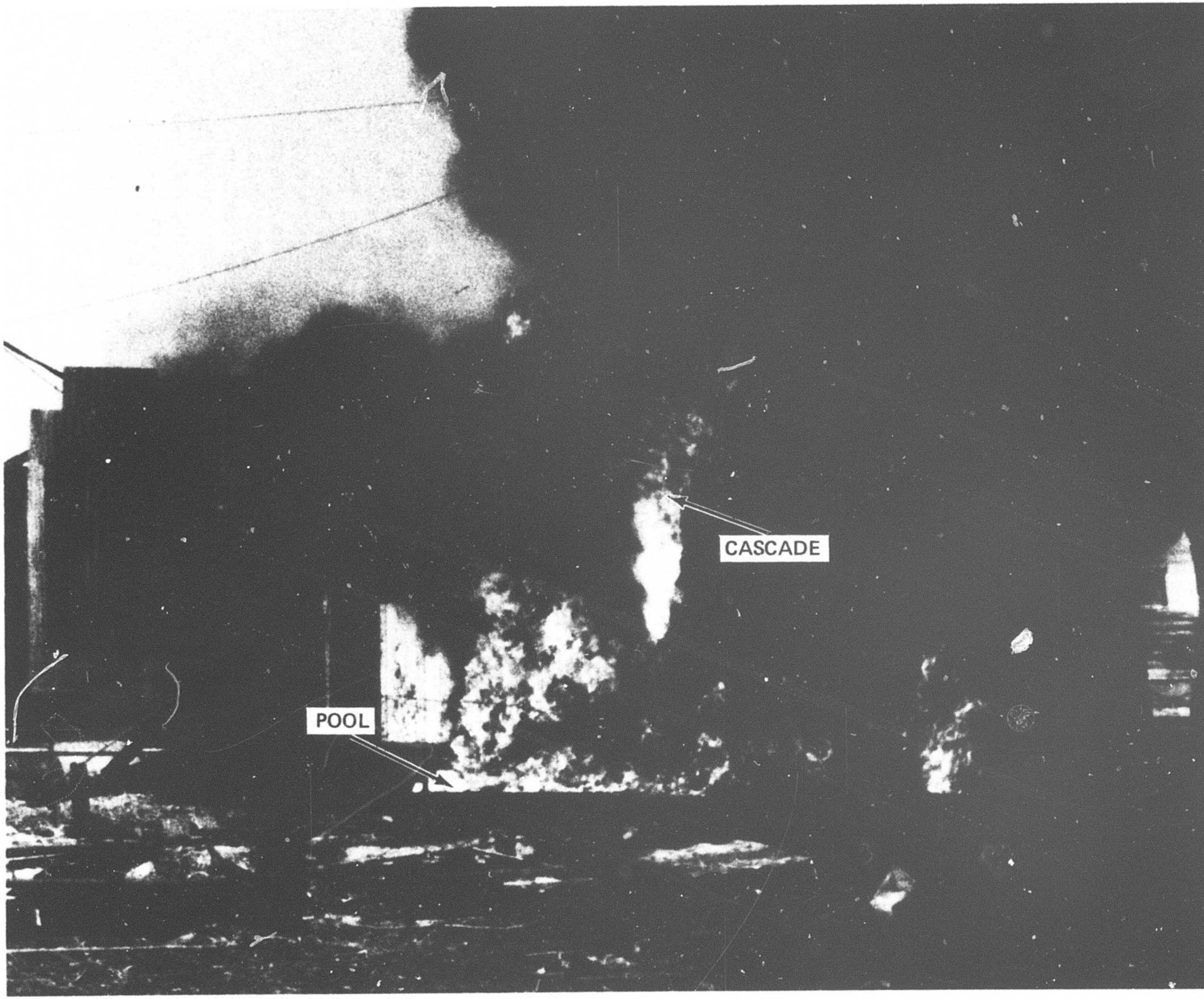


FIG. 2.11 COMBINATION CASCADE PLUS POOL FIRE LOW WIND CONDITIONS (TEST 13)

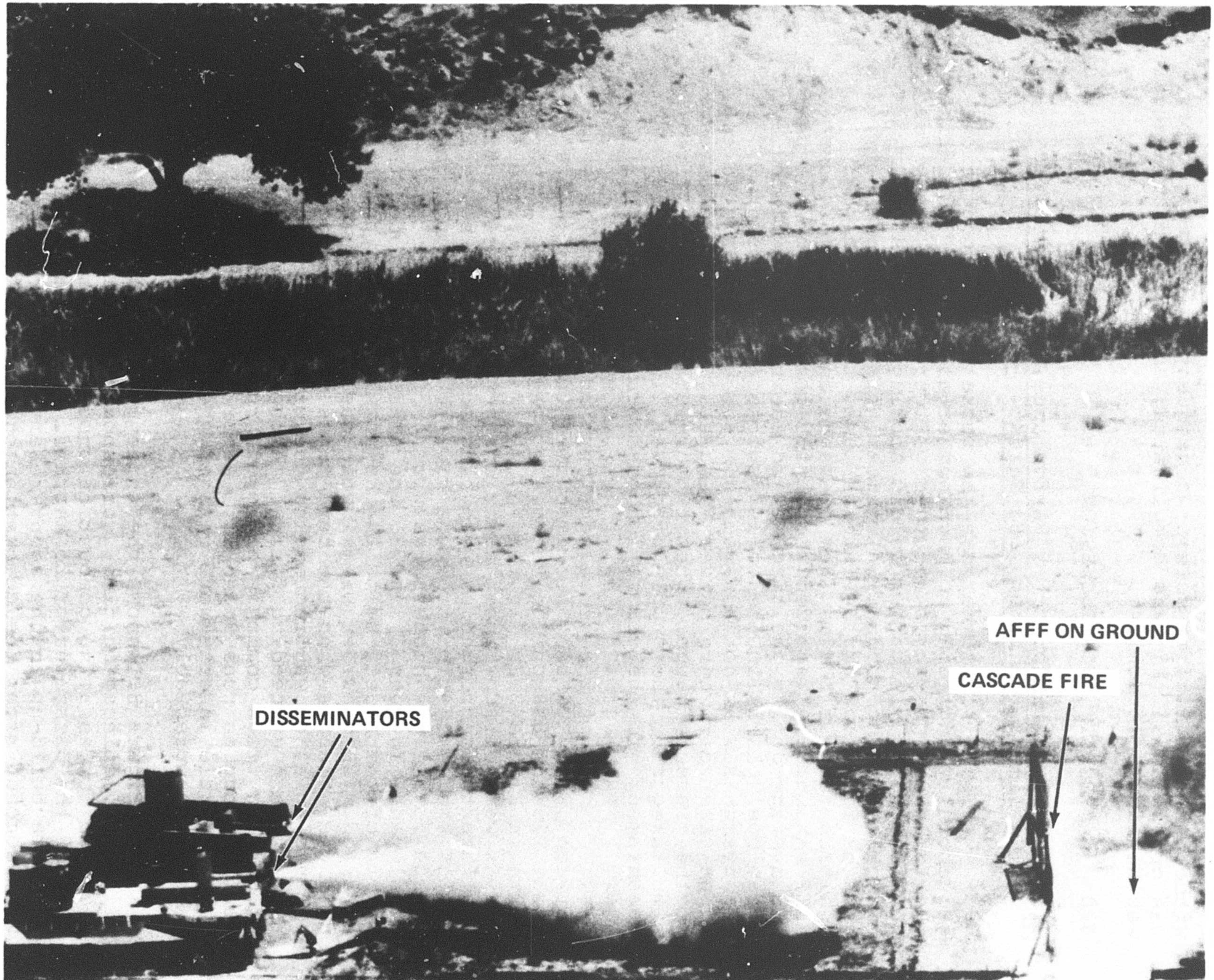


FIG. 2.12 TYPICAL 20 FOOT CASCADE FIRE IN PROGRESS AT SITE 300. THE TWO DISSEMINATORS ARE DISCHARGING SIMULTANEOUSLY (TEST 34)

without relocating the screen; consequently, the trajectory was crosswind, aiming was complicated, and uniform coverage was difficult to achieve.

3.0 RESULTS AND DISCUSSION

3.1 Disseminator Motor Performance Propellant Burn Times, Pressures, and Thrust

Table 3.1 summarizes the rocket firing conditions sequentially according to burn number and Figure 3.1 defines the times and pressures recorded. Figure 3.1 is a typical portion of the visicorder record showing the pressure histories of the combustion chamber, the agent reservoir, and the injection port. In each case, the time from ignition to half the maximum pressure and the time above half maximum are recorded along with pressures for the peak and average during the time period shown. As indicated by occasional blanks in the table, successful pressure measurements were not always achieved, particularly in the agent reservoir where powder frequently plugged the passage of the pressure gauge. When two disseminators were fired simultaneously, the supply of gauges limited pressure measurements to the combustion chamber.

Most of the propellant burning times (t_b) are between .8 and .9 sec, corresponding to pressures between about 720 and 830 psi on the design pressure vs burning rate curve in Figure 2.2. In runs 5, 10, 23, and 36, propellant grains were fired without agent in the disseminator. Since the thrust director holes were plugged during these firings, all of the combustion products have to leave through the carbon nozzle and higher pressures and burning rates developed. In runs 33 and 36 the pressures exceeded the limits of the safety-bolts in the nozzle head which then departed with considerable kinetic energy. Test 20 occurred during a sequence when the burn times were increasing because ablation was increasing the carbon-nozzle throat area on each succeeding firing. Although within the range of burning times commonly employed, run 10 burned only about half as long as runs 9 and 11. After run 11, the carbon-nozzle inserts were changed whenever the burning time increased appreciably.

Figure 3.1 shows the three pressure curves are slightly displaced in time; corresponding to the lag required for escaping combustion products to move from one part of the disseminator to another. For example, the pressure build-up in the agent reservoir occurs 50 to 75 milliseconds after the combustion chamber and another 50 milliseconds are required for pressure and presumably the agent to reach the injector port. Since the period from

TABLE 3.1 EXTINGUISHMENT TESTS WITH MONNEX AND PK POWDERS

BURN NO.	FIRE TYPE (1)	AGENT		MODE OF APPLICATION (2)	ORIENTATION		WIND VELOCITY MPH	AFFF APPLIED GAL	EXTINGUISHED
		TYPE	AMOUNT LBS.		NOZZLE (3)	ROCKET (4)			
1	POOL ON H_2O	MONNEX SLURRY		ROCKET 1	H	1	7.0	NONE	NO
1A	POOL ON H_2O	MONNEX POWDER	19	HAND	NONE	NONE		NONE	NO
2	POOL ON H_2O	MONNEX POWDER	11	ROCKET 2	V	1	7.8	NONE	NO
3	10' CASCADE H_2O IN PAN	MONNEX POWDER	19	HAND	NONE	NONE	9.0	NONE	NO
4	10' CASCADE H_2O IN PAN	MONNEX POWDER	12	ROCKET 2	V	2	10.3	NONE	NO
5	10' CASCADE H_2O IN PAN	–	NONE	ROCKET 2	V	3	–	NONE	NO
6	10' CASCADE H_2O IN PAN	PKP		HAND	NONE	NONE		NONE	NO
7	10' CASCADE DRY PAN	MONNEX POWDER	17.3	ROCKET 3	V	4	9.5	12	YES
8	10' CASCADE DRY PAN	PKP	19	ROCKET 3	V	4	14.7	10	NO
9	10' CASCADE DRY PAN	PKP	20	ROCKET 3	H	4	15.5	10	YES
10	10' CASCADE DRY PAN	–	NONE	ROCKET 3	H	4	16.1	10	YES
11	CASCADE + POOL	MONNEX POWDER	13	ROCKET 3	H	4	14.0	10	NO
12	POOL ON H_2O	MONNEX POWDER	19	HAND	NONE	NONE		10	NO
13	CASCADE + POOL	MONNEX POWDER	16	ROCKET 3	H	4	10.0	10	NO
14	POOL ON H_2O	MONNEX POWDER	12	ROCKET 3	H	4	11.3	10	NO
15	POOL ON H_2O	MONNEX POWDER	13.8	ROCKET 3	H	5	12.7	10	NO
16	POOL ON H_2O	MONNEX POWDER	15	ROCKET 3	H	5	12.9	10	NO
17	POOL ON ROCKS	MONNEX POWDER	19	HAND	NONE	NONE		NONE	NO
18	POOL ON ROCKS-50%	MONNEX POWDER	19	HAND	NONE	NONE		NONE	YES
19	POOL ON ROCKS-30%	PKP	25	HAND	NONE	NONE		NONE	YES
20	POOL ON ROCKS-15%	PKP	26	HAND	NONE	NONE		NONE	NO

(1) BURN NO. 1 WAS JP5,ALL OTHERS WERE JP4. % = FRACTION OF FIRE AREA OCCUPIED BY EXPOSED ROCKS.

(2) ROCKET 1 = EQUIPPED WITH PLUNGER TO PUMP SLURRY
ROCKET 2 = FIRST DRY POWDER DESIGN
ROCKET 3 = 2ND DRY POWDER DESIGN WITH ENLARGED DELIVERY TUBE

TABLE 3.1 (CON'T.)

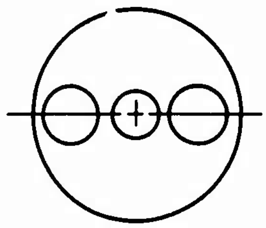
BURN NO.	FIRE TYPE (1)	AGENT		MODE OF APPLICATION (2)	ORIENTATION		WIND VELOCITY MPH	AFFF APPLIED GAL	EXTING-UISHED
		TYPE	AMOUNT LBS		NOZZLE (3)	ROCKET (4)			
21	POOL ON ROCK -15%	MONNEX POWDER	19	HAND	NONE	NONE		NONE	NO
22	POOL ON ROCK-30%	MONNEX POWDER	14	ROCKET 3	H	5	10.3	NONE	NO
23	POOL ON ROCK-30%	MONNEX POWDER	14	ROCKET 3	H	5	12.7	NONE	NO
24	POOL ON ROCK-50%	MONNEX POWDER	14	ROCKET 3	H	5	10.1	NONE	NO
25	POOL ON ROCK-50%	MONNEX POWDER	15 + 14	2 ROCKETS BROADSIDE	H	6		15	NO
26	1/2 POOL	MONNEX POWDER	16 + 14	2 ROCKETS BROADSIDE	H	6		NOT MEAS-URED	NO
27	20' CASCADE	MONNEX POWDER	–	ROCKET 3 END ON	H	7	6.3	NONE	NO
28	20' CASCADE	MONNEX POWDER	14.5	ROCKET 3 END ON	H	7	11.8	DOWN WIND SIDE OF SCREEN COATED	NO
29	20' CASCADE	MONNEX POWDER	? 16	2 ROCKETS BROADSIDE	H	8	8.6	DOWN WIND SIDE OF SCREEN COATED	NO
30	20' CASCADE	MONNEX POWDER	14 15	2 ROCKETS BROADSIDE	H	8	7.8	APPLIED THROUGH-OUT TEST	NO
31	20' CASCADE (9 GPM)	MONNEX POWDER		2 ROCKETS BROADSIDE	H	8	7.5	APPLIED THROUGH-OUT TEST	NO
32	10' CASCADE (3.8 GPM)	MONNEX POWDER	15 15.5	2 ROCKETS BROADSIDE	H	9	8.8	APPLIED THROUGH-OUT TEST	YES
33	10' CASCADE (6.6 GPM)	NONE	0	ROCKET 3	H	3	5.0	APPLIED THROUGH-OUT TEST	NO
34	10' CASCADE (6.7 GPM)	MONNEX POWDER	15 14	2 ROCKETS BROADSIDE	H	9		APPLIED THROUGH-OUT TEST	NO
35	10' CASCADE (6.7 GPM)	MONNEX POWDER	16 16	2 ROCKETS BROADSIDE	H	9		APPLIED THROUGH-OUT TEST	NO
36	10' CASCADE (6.7 GPM)	NONE	0 0	2 ROCKETS BROADSIDE	H	9		APPLIED THROUGH-OUT TEST	NO

TABLE 3.1 CON'T.

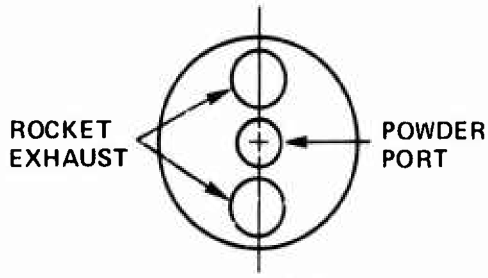
		COMBUSTION CHAMBER				AGENT TANK				EJECTOR			
THRUST PSI	BURN NO.	P_C PEAK PSI	P_C AVG PSI	t_1 SEC	t_b SEC	P_t PEAK PSI	P_t AVG PSI	t_1 SEC	$t_{1/2}$ SEC	P_i PEAK PSI	P_i AVG PSI	t_1 SEC	$t_{1/2}$ SEC
910	1	1310	1170	0.08	0.83	1280	1150	0.08	0.82	1040	920	0.08	0.82
1300	2	1830	1085	0.05	0.84	560	455	0.22	0.84	190	105	0.13	0.82
	3												
870	4	980	850	0.06	1.06	450	380	0.1	1.07	150	170	0.14	1.0
	5												
950	7	940	710	0.09	1.21	910	610	0.44	0.98				
1250	8	855	660	0.12	1.3	830	575	0.51	1.11			0.16	0.3
510	9	530	340	0.1	1.97	150	130	0.68	1.51			0.41	1.5
1280	10	1325	1060		0.88								
450	11	515	325	0.13	2.1[illegible]	160	130	0.17	2.03			0.33	1.91
1370	13	1470	1237	0.12	0.8	470	380	0.18	1.1	165	125	0.29	0.67
1260	14	1430	1230	0.11	0.8	290	200	0.45	1.16			0.29	0.67
1375	15	1510	1290	0.08	0.74					150	90	0.24	0.68
1350	16	1418	1190	0.11	0.8	300	230	0.58	0.65	154	125	0.26	0.7
1200	22	1225	1020	0.12	0.92	470	385	0.17	0.92	125	10[illegible]	0.26	0.82
1330	23	1410	1195	0.08	0.81	614	475	0.125	0.83	168	132	0.29	0.66
1280	24	1325	1055	0.12	0.9	620	500	0.18	0.88	135	115	0.33	0.75
1475	25	1530	1320	0.14	0.73	630	512	0.2	0.7	95	80	0.34	0.54
1470	26	1465	1230	0.13	0.76	560	492	0.18	0.76	120	92	0.38	0.54

TABLE 3.1 (FOOTNOTES CONT.)

(3) ORIENTATION OF NOZZLE

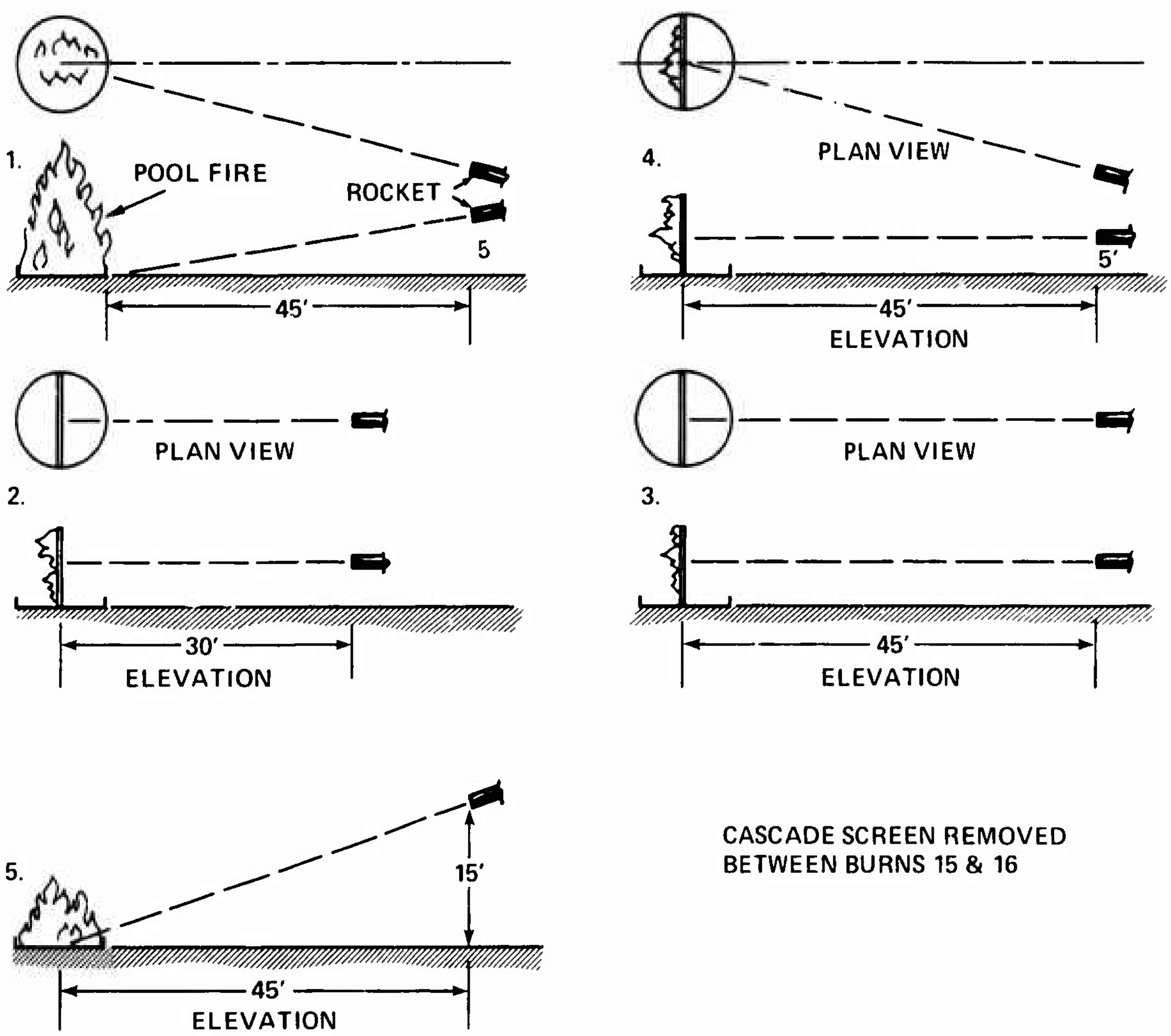


H = HORIZONTAL



V = VERTICAL

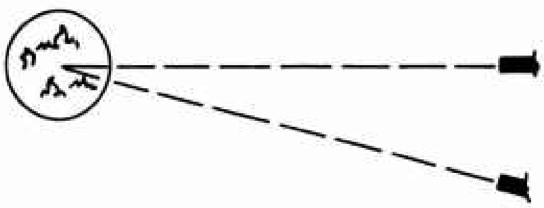
(4) ORIENTATION OF ROCKET



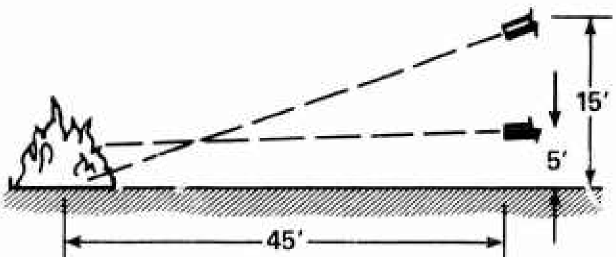
CASCADE SCREEN REMOVED
BETWEEN BURNS 15 & 16

TABLE 3.1 (FOOTNOTES CON'T.)

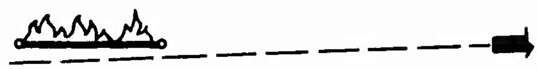
ORIENTATION OF ROCKET CON'T.



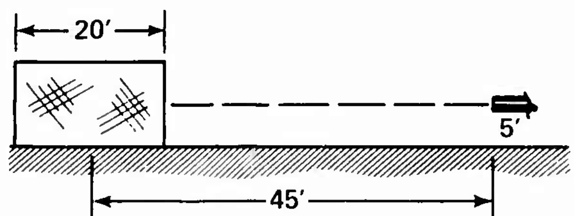
6. PLAN VIEW



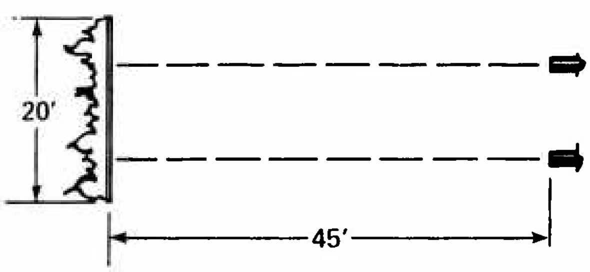
ELEVATION



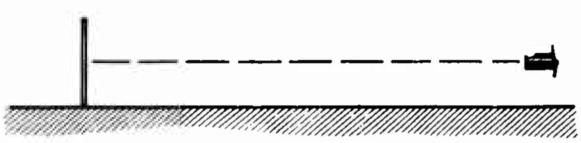
7. PLAN VIEW



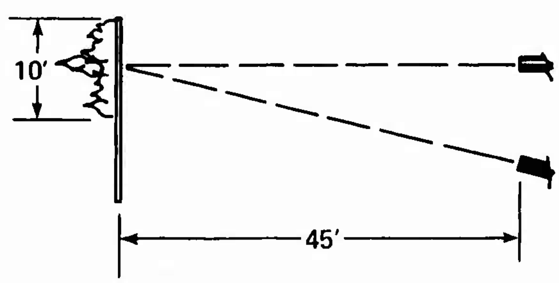
ELEVATION



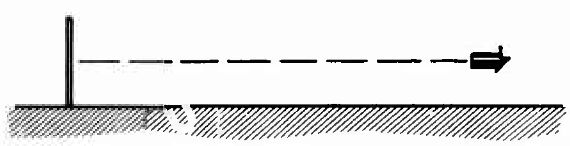
8. PLAN VIEW



ELEVATION



9. PLAN VIEW



ELEVATION

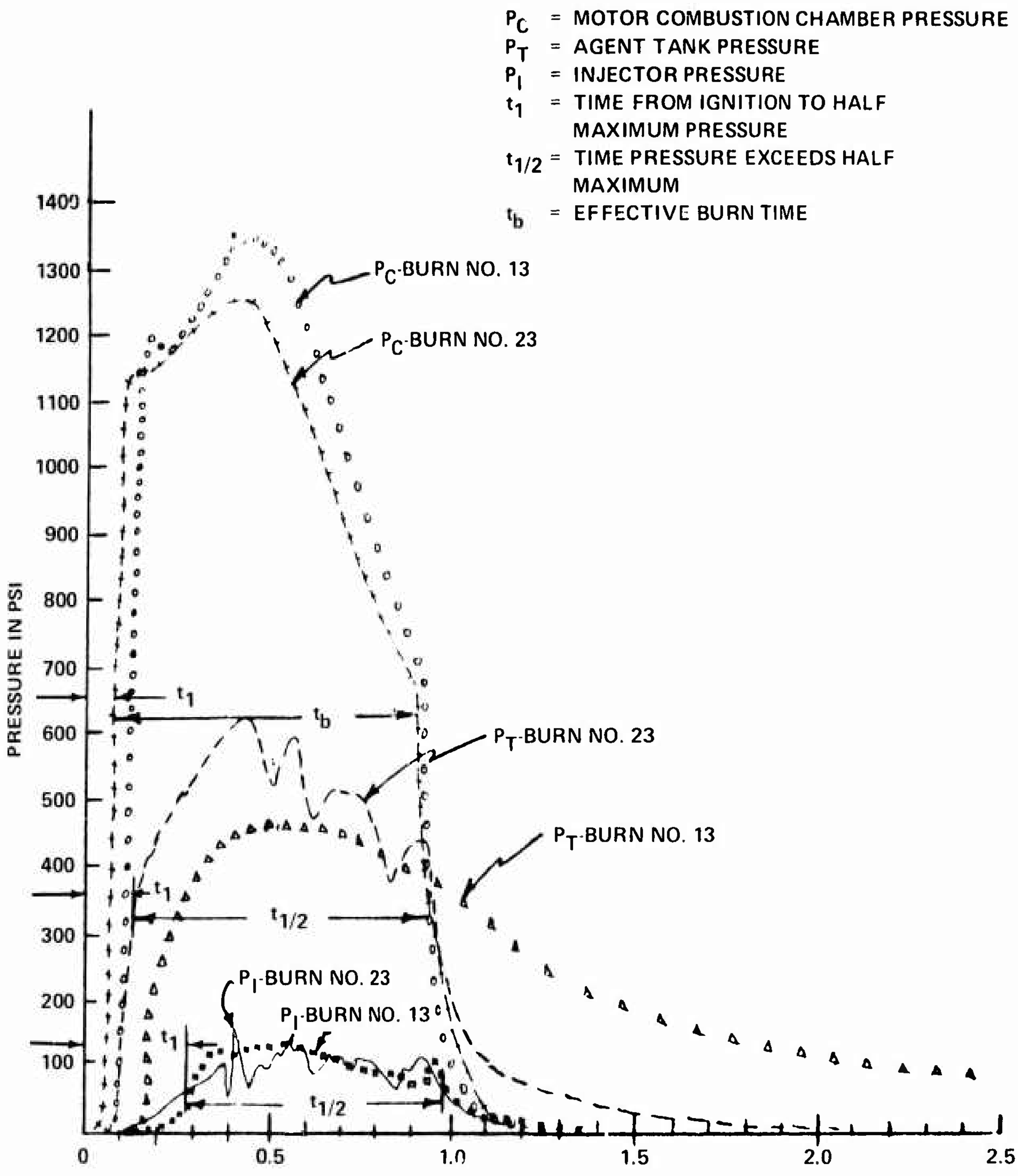


FIG. 3.1 COPY OF VISACORD‹ R RECORDS SHOWING THE PRESSURES DEVELOPED AT VARIOUS POSITIONS IN THE DISSEMINATOR DURING TESTS 13 AND 23. P_C = PRESSURE IN THE ROCKET-MOTOR CHAMBER, P_T = PRESSURE IN AGENT RESERVOIR, AND P_I = EJECTOR PRESSURE.

ignition to vigorous propellant burning is also about .1 second, the first powder can be expected about .2 second after ignition. All three curves exhibit similar $t_{1/2}$ times; however, the agent reservoir curve has a low-pressure tail that extends beyond the other curves presumably due to the time required to bleed down the gas in the larger volume. In calculating discharge times it was assumed that significant powder ejection did not occur throughout this trailing portion of the curve.

Table 3.1 lists the thrust levels developed by the rocket exhaust, and as would be expected, the largest values correspond to the shortest burning times.

3.2 Agent Dissemination

This section deals with the temporal and spatial features of the cloud from the instant powder is emitted until there is no further interaction in the combustion zone because either the fire has been extinguished or the agent is depleted. Most of the data is derived from high-speed motion pictures.

3.2.1 Temporal History

Figure 2.9 is a series of three 35 mm photographs, covering the extinguishment of the burn NR 9 cascade fire. In view (2.9.1) the powder has gone about 30 ft, i.e., two-thirds of the way to the fire, and according to Table 3.2 has a velocity of about 70 mph. In view (2.9.2), the powder has completely enveloped the fire, the disseminator is still discharing vigorously, and the cloud is well over 60 ft long. Finally view (2.9.3) shows the fire extinguished, although fuel vapors are still coming off the hot metal screen and the cloud has gone by. The temporal history was obtained by plotting such powder envelopes from the motion picture coverage as a function of time. Two factors complicated the analysis and introduced some uncertainty in the time scale. Mainly, it is difficult to tell from the photographs when significant agent dissemination commences and when it stops. First the white cloud of combustion products from the rocket motor is indistinguishable in the photographs from the agent, therefore, we have used the times from Table 3.1 to estimate when agent starts to emerge. Synchronization of the photographic and visicorder trace is based on the firing of the squib in the ignitor because it is visible in both records. Second, the end-point time is also obscured because powder continues to emerge from the disseminator after the propellant grain has been consumed. Figure 2.5 shows such a burned out condition and the wisps of powder that continued after the end of vigorous pumping. The

TABLE 3.2

TEMPORAL HISTORY OF AGENT

Test No.	Time For Powder To Go From Nozzle To Fire Sec.	Time For Powder To Fill Flame Volume Sec.	Powder Discharge Time From Photos Sec.	Residence Time of Powder In Fire Zone Sec.	Powder Velocity Average Between Nozzle and Fire FT $Sec.^{-1}$	Powder Velocity MPH
1	.29	.26	.82	1.4	141	96
2	.24	.17	2.9	5.6	123	83
4	.17	.16	2.5	4.9	267	182
5	.23	.14	.68	1.7	267	182
8	.47	.23	1.1	1.9	101	69
9	.46	.16	2.1	1.1	103	70c
10	.37	.15	.86	1.6	154	105
11	.46	.65	1.8	2.2	94	64
13	.37	.40	1.5	2.4	142	97
14	.33	.45	1.7	3.9	143	97
15	.32	.45	1.3	2.6	147	100
16	.38	.43	1.4	2.5	127	87

discharge times listed in Table 3.2 do not include the tailing of Figure 2.5 but assume an end-point when the first reduction in pumping rate is visible.

Figure 3.2 shows the progression of the cloud front plotted as a function of flight time between nozzle and fire, i.e., the data that provide a basis for computing the initial cloud velocities recorded in Table 3.2. Several features are apparent; first, as would be expected, the cloud slows down with distance. Second, runs 8, 9, and 11 are considerably slower than the others presumably because the nozzle throat was ablating away, thereby increasing the area and reducing the pressure. Third, run 10 which had no powder, or opening to the agent reservoir, developed sufficient pressure to compensate for the enlarged holes and reached the higher velocity group. Fourth, there appears to be no inherent difference between PKP and Monnex in their velocities. Fifth, the single slurry tests developed an intermediate velocity between the high- and low-dry powder values. As indicated in Table 3.2, average velocites range from about 70 to 180 mph.

3.2.2 Spatial History

Because of the high cloud velocity compared to the buoyancy currents in the combustion column, the rocket component dominates the collision between powder and fire. Figure 2.9.2 shows the cloud continuing through the combustion zone with only a slight upward enlargement and dispersion of the powder. Somewhat larger dispersions occurred under lower ambient wind conditions but in all cases the powder continues and deposits for several hundred feet beyond the fire. Frequently a large ball of fire erupts during the initial encounter between powder and flames in the manner commonly observed with dry chemicals. Figure 3.3.1 shows this energy spike in a typical radiometer curve and Figures 3.3.2, 3.3.3 and 3.3.4 show cloud-fire collisions for the three types of fires employed, i.e., pool, cascade, and cascade plus pool. These cloud outlines were traced from the high-speed motion pictures at the times indicated. Since the combination fire involves the highest burning rate and therefore the greatest buoyance columns, it is natural for the powder dispersion to be the greatest in this case.

3.2.2 Powder Concentration

Estimates of powder concentration in the cloud are limited to rough approximations that depend on the assumptions about agent distribution. In the simplest model, assuming a constant discharge rate and a uniform powder distribution through a conical cloud, the density (D)

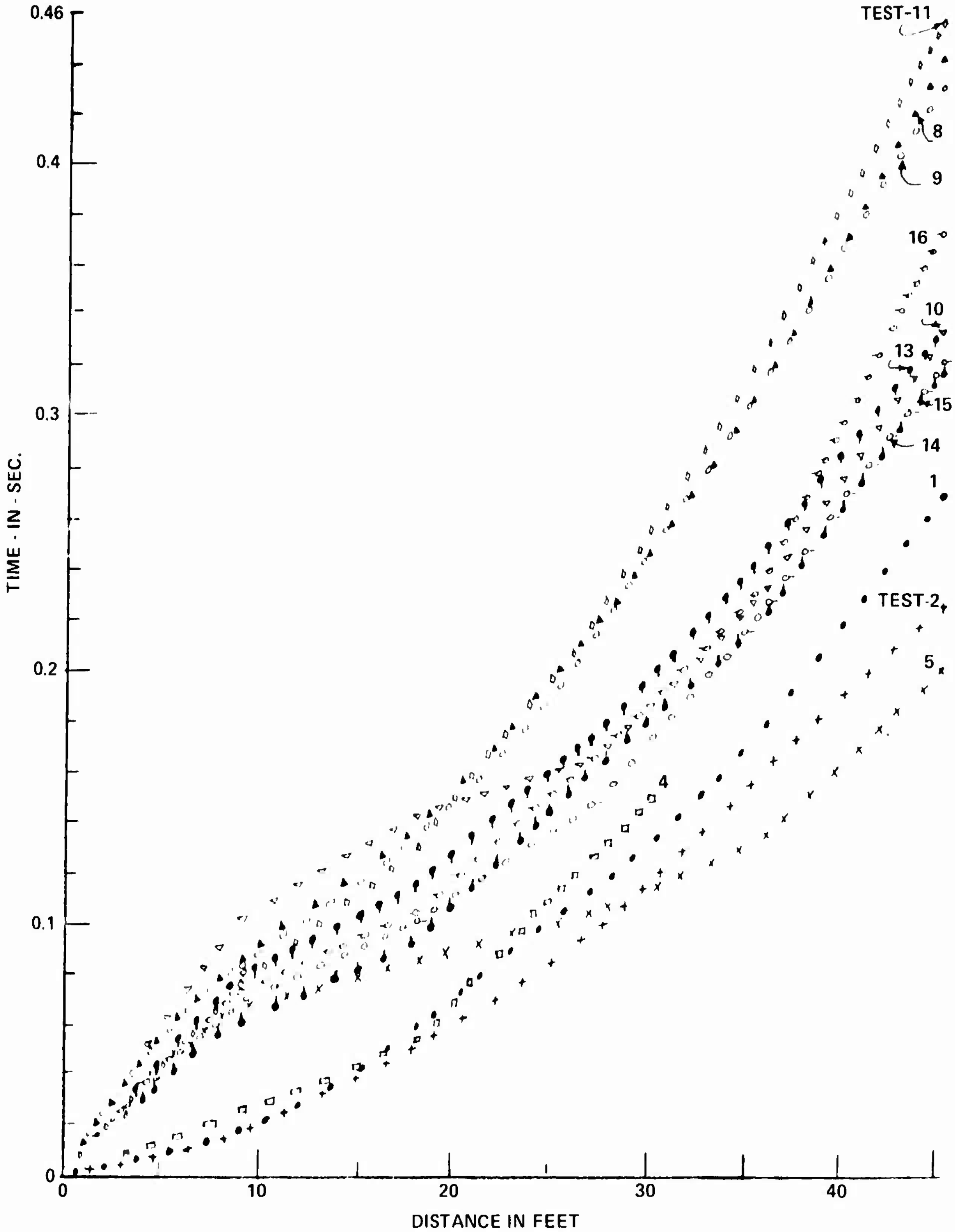


FIG. 3.2 AGENT CLOUD FRONT AS A FUNCTION OF TIME AFTER ROCKET IGNITION.

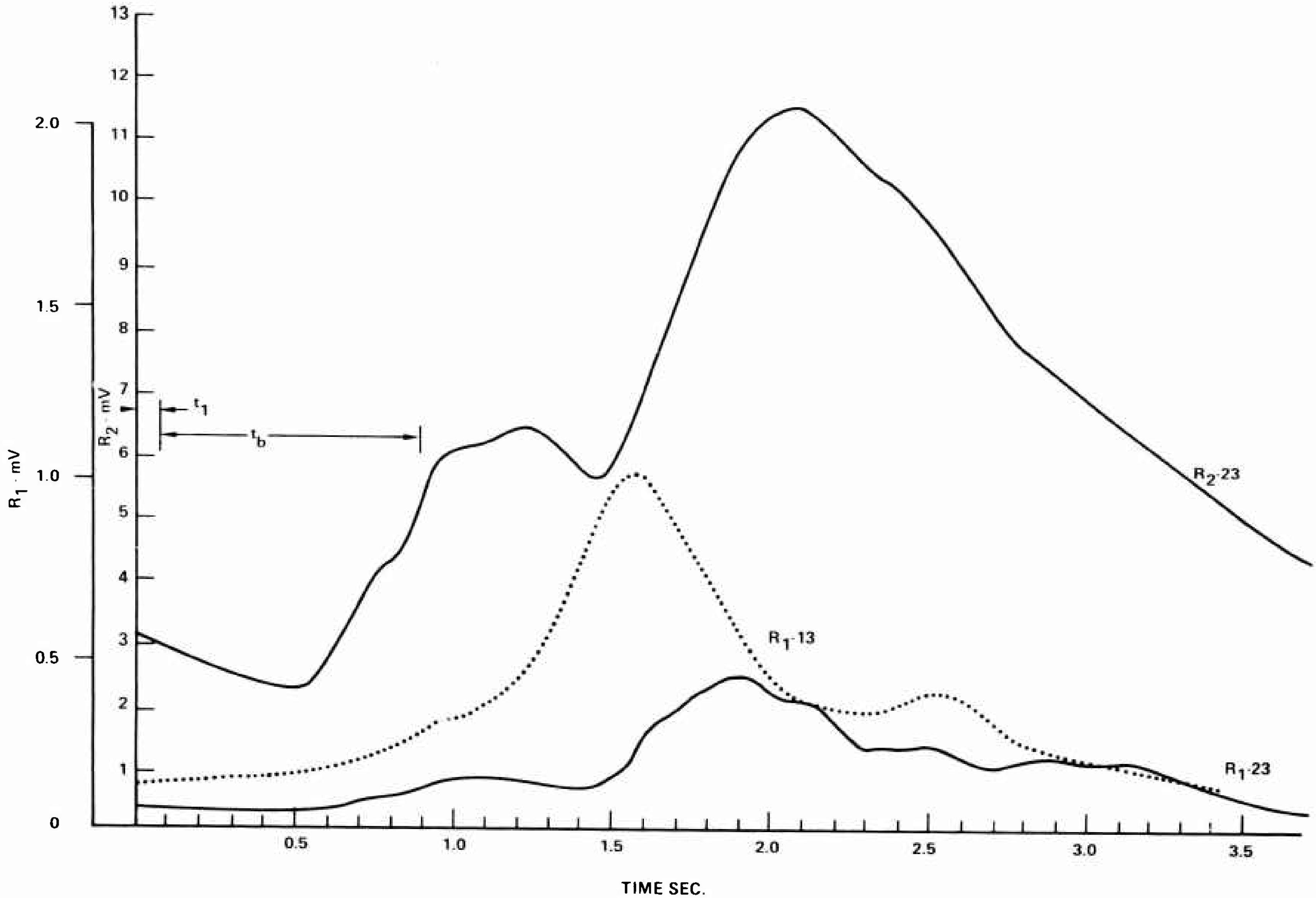
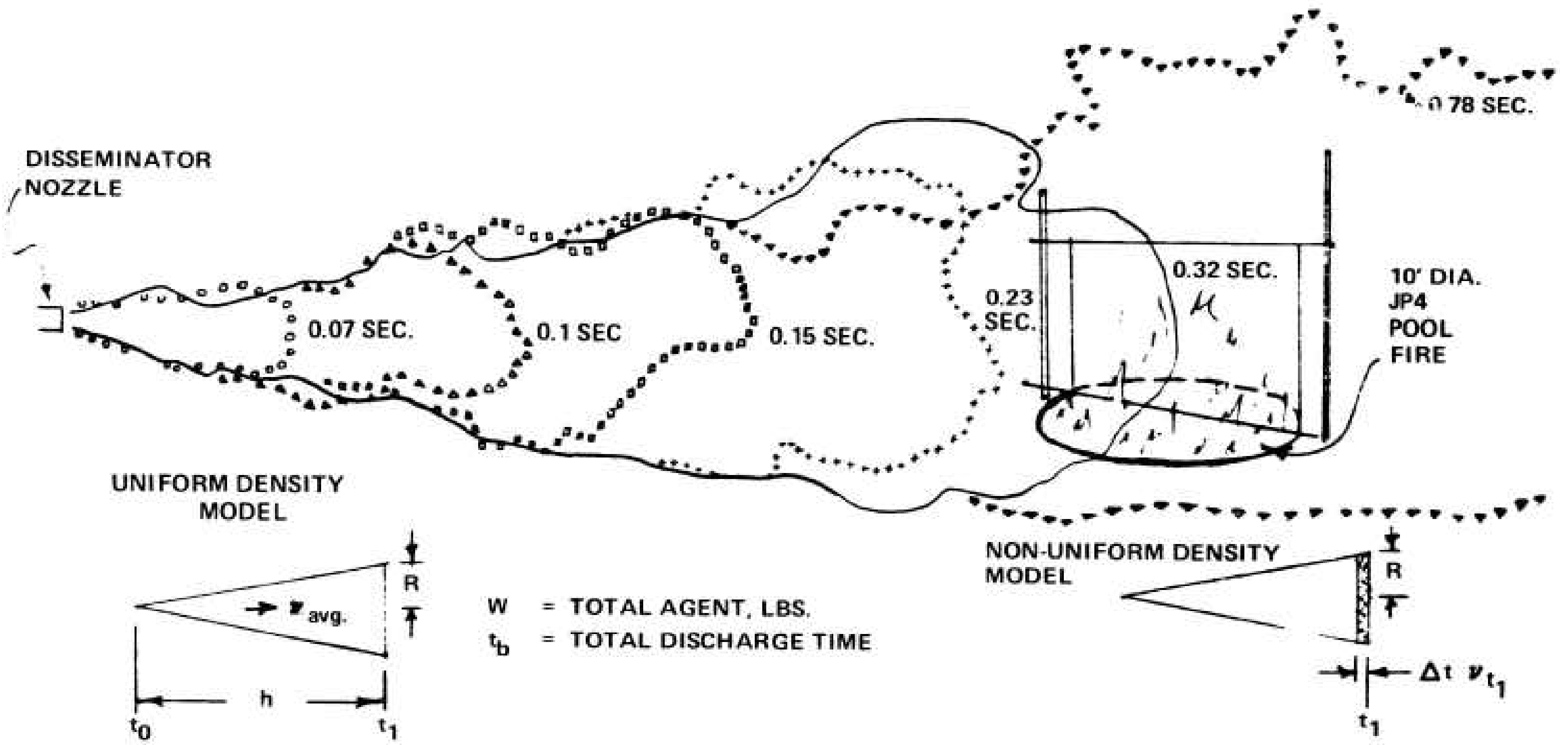


FIG. 3.3.1 THERMAL RADIATION PULSE RECORDED BY RADIOMETERS WHILE POWDER INTERACTS WITH FIRE.

TEST NO. 14



$W = 12$

$R = 10$

$t_b = 1.7$ SEC.

$\nu_{avg} = 143$ FT SEC^{-1}

$\nu_{t_1} = 100$ FT SEC^{-1}

DISCHARGE RATE $= \dfrac{W}{t_b}$

POWDER DISCHARGED $= \dfrac{W t_1}{t_b}$

CONICAL VOLUME $= \dfrac{\pi}{3} R2\, h = \dfrac{\pi}{3} R^2\, t_1 \nu_{avg}$

$h = t_1 \nu_{avg}$

POWDER DENSITY $= \dfrac{\frac{wt_1}{t_b}}{\frac{\pi}{3} R^2 t_1 \nu_{avg}} = \dfrac{3W}{\pi R^2 t_b \nu_{avg}}$

$D = 4.7 \times 10^{-4}$ lbs FT^{-3}

DISCHARGE RATE $= \dfrac{W}{t_b}$

POWDER DISCHARGED $= \dfrac{W\Delta t}{t_b}$

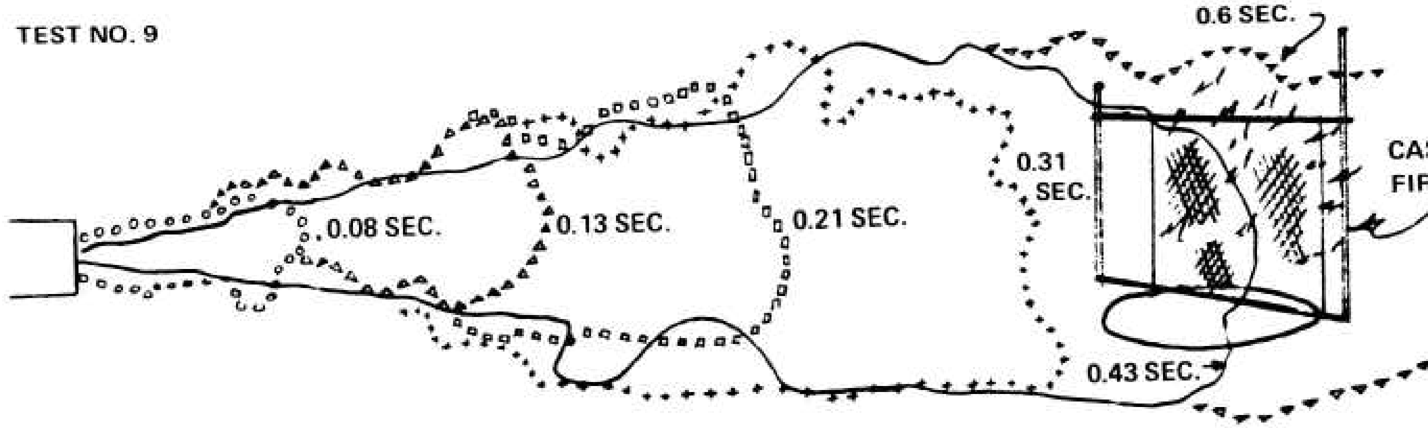
INCREMENTAL VOLUME $= \pi R^2 \Delta t \ \nu t_1$

POWDER DENSITY $= \dfrac{\frac{W\Delta t}{t_b}}{\pi R^2 \Delta t \ \nu t_1} = \dfrac{W}{t_b \pi R^2 \ \nu t_1}$

$D = 2.3 \times 10^{-4}$ lbs FT^{-3}

FIG. 3.3.2 OUTLINE OF AGENT CLOUD AT VARIOUS TIMES DURING TRANSIT FROM DISSEMINATOR TO POOL FIRE.

TEST NO. 9



$W = 20$ LBS
$R = 8'$
$t_b = 2.1$ SEC
$\nu_{avg} = 103$ FT SEC^{-1}
$\nu_{t_1} = 80$ FT SEC^{-1}

UNIFORM DENSITY MODEL

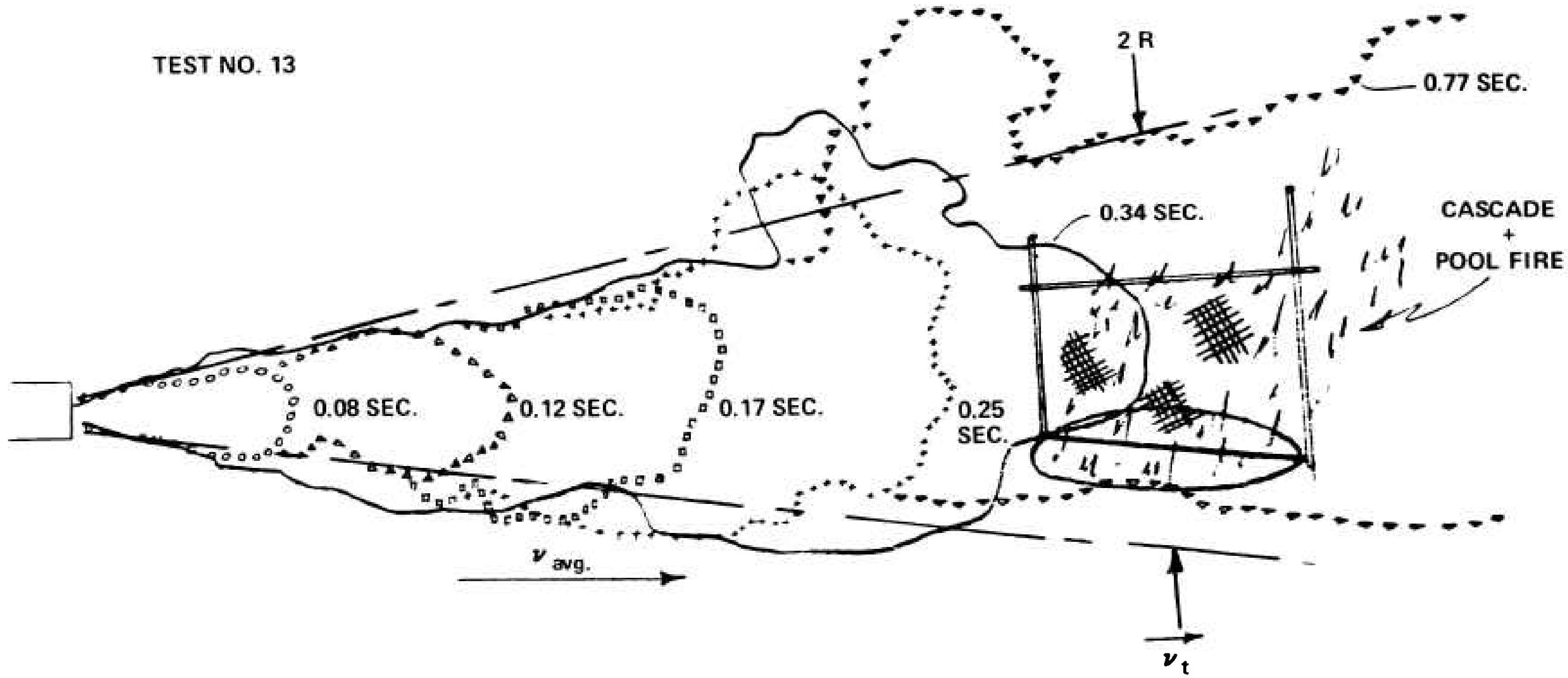
$$D = \frac{3W}{\pi R^2 t_b \nu_{avg}} = \frac{3 \cdot 20}{\pi \cdot 64 \cdot 2.1 \cdot 130} = 1.38 \times 10^{-3} \text{ LBS FT}^{-3}$$

NON-UNIFORM DENSITY MODEL

$$D = \frac{W}{\pi R^2 t_b \nu_t} = \frac{20}{\pi \cdot 64 \cdot 2.1 \cdot 80} = 5.9 \times 10^{-4} \text{ LBS FT}^{-3}$$

FIG. 3.3.3 CLOUD OUTLINES DURING CASCADE FIRE SHOW VERY LITTLE DEFLECTION DUE TO COLLISION WITH CONVECTION COLUMN.

TEST NO. 13



$W = 16$ LBS
$R = 9.5$ FT
$T_b = 1.5$ SEC
$\nu_{avg} = 142$ FT SEC^{-1}
$\nu_{t_1} = 111$ FT SEC^{-1}

UNIFORM DENSITY MODEL

$$D = \frac{3W}{\pi R^2 t_b \nu_{avg}} = \frac{3.16}{\pi 90.25 \cdot 1.5 \cdot 142} = 7.9 \times 10^{-4} \ \frac{LBS}{FT^3}$$

NON-UNIFORM DENSITY MODEL

$$D = \frac{W}{\pi R^2 t_b \nu_t} = \frac{16}{\pi 90.25 \cdot 1.5 \cdot 111} = 3.4 \times 10^{-4} \ \frac{LBS}{FT^3}$$

FIG. 3.3.4 CLOUD OUTLINES FOR COMBINATION POOL PLUS CASCADE FIRE EXHIBIT SOME DEFLECTION AFTER COLLISION WITH FIRE.

becomes $D = \frac{3Wt_1}{t_b \pi R^2 h}$ or $\frac{3W}{t_b \pi R^2 v_{avg}}$ where W = the total weight of agent discharged, t_b = the discharge time, t_1 = the transit time from nozzle to fire at average velocity v_{avg}, and R = the cross sectional radius of the cloud as indicated in the first derivation in Figure 3.2.2. Densities computed by this model range from 1.38×10^{-3} for the longer discharge times to 7.9×10^{-4} lb/ft^3 for the shortest times. The second model shown in Figure 3.3.2 allows for a change of density along the trajectory as the cloud spreads out and slows down. Following the derivation in Figure 3.3.2, the density becomes $D = \frac{W}{t_b \pi R^2 v_{t_1}}$ where v_{t_1} is the velocity at time t_1. Without the correction for velocity, these densities are only 1/2 those in the uniform distribution model. When cloud velocities at the time of collision with the combustion zone are introduced, the nonuniform density model yields concentrations ranging from 5.9×10^{-4} to 3.4×10^{-4} for the case already examined by the uniform density model.

Reliable critical application concentrations for extinguishment with PKP and Monnex are not available but estimates based on other agents and the reported relative effectiveness of these agents to PKP and Monnex indicate the concentrations achieved with the rocket disseminator are a bit low for extinguishment. Without a reliable relationship between the agent requirement and the fire intensity, such estimates are of dubious value but they are supported by the obvious fact that the rocket disseminator cloud generally did not completely extinguish the fire.

3.2.4 Residence Time in Fire Zone

The powder available to interact with the reactive species in the combustion zone depends on both the concentration and the residence time; i.e. the number of particles and the time they remain in the reaction zone. Residence times can be defined in terms of either the individual particles or the cloud of particles. In Table 3.2 the times listed are for the entire cloud to pass through the fire zone as determined from motion pictures.

If all of the powder passed through the fire area and followed the same velocity schedule, the residence time would equal the discharge time; however, after the propellant is exhausted, some of the powder between the nozzle and the fire drifts with the ambient wind and may or may not reach the fire area in an effective pattern. Typical values of residence time in the fire area range from 1.6 to 5 sec.

3.2.5 Slurry vs Powder Dissemination

Three factors led to the emphasis on dry powder in preference to the slurry mode of dissemination. First, both systems disseminate about the same amount of agent per grain but the powder required no tedious mixing and was much easier to load. Second, the powder did not stick to every surface in its path like the slurry. Figure 3.4 shows the agent buildup on a thermocouple support and its guy wires. Every surface in the rocket's path develops a stucco coating, which, of course, decreased in thickness with distance from the rocket. With powders, some coating occurs particularly in holes such as the input to the thrust gauge 20 ft in front of the rocket, however, most of the powder continues on to the fire. Finally, in the initial comparison, the dry powder appeared to be as effective as the slurry in extinguishment. There was some concern that exposure to the hot rocket blast would prematurely decompose the potassium bicarbonate and reduce its effectiveness particularly when combined with urea to form the Monnex carbamic powder. Previous experience with slurries had established that materials considerably more sensitive than these fire extinguishing agents could be dispensed through the rocket exhaust without alteration. Microscopic examination of Monnex collected from a dry powder discharge before the powder reached the test fire indicates some change in the particle size distribution as shown in Figure 3.5.1 and 3.5.2. The sample of virgin powder Figure 3.5.1 contains considerably more small particles than the discharge sample Figure 3.5.2. Since some small particles survived the rocket blast it is not clear whether the change in distribution indicates decomposition of some small particles or a particle size bias in the collection procedure.

3.3 Effects of Experimental Parameters on Extinguishment

This section is concerned with parameters employed to describe the fire characteristics, environment, and suppression agent. Unfortunately, most of the tests did not achieve extinguishment; consequently, it is impossible to establish quantitatively the importance of the variables involved.

3.3.1 Type of Fire

Despite the comparable areas and burning rates for the pool and spray fires, i.e., 78 ft^2 burning at 9.8 gpm and 80 ft^2 burning at 6.6 gpm respectively, the summary in Table 3.1 shows a marked differenke in the extinguishments achieved. No fires involving burning pools of fuel were extinguished but early results with the cascade fires, i.e.,

FIG. 3.4 SLURRY DEPOSIT ON PIPE AND WIRES AFTER A SINGLE DISCHARGE

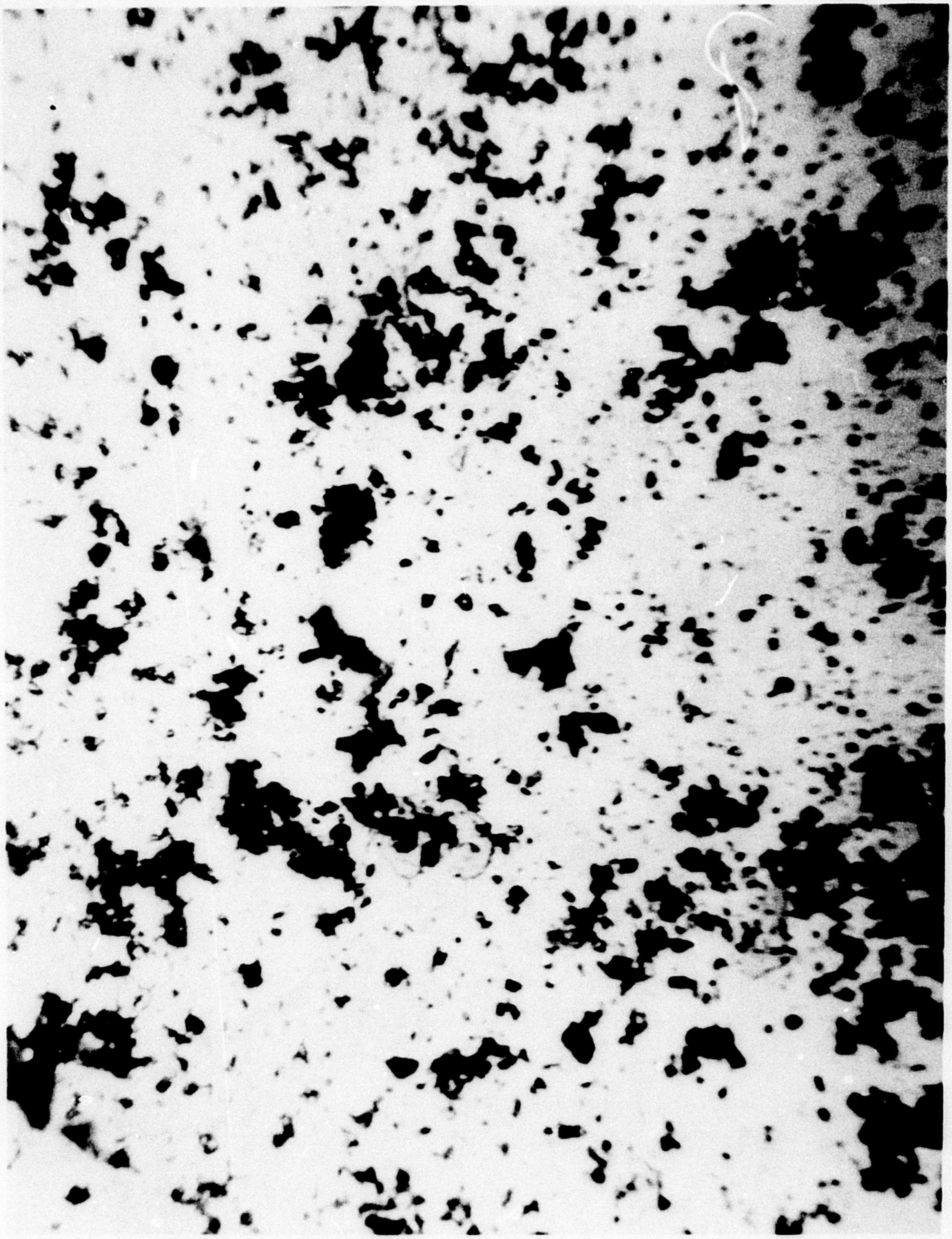


FIG. 3.5.1 PHOTOMICROGRAPH OF VIRGIN MONNEX POWDERS, MAGNIFICATION = 360X

FIG. 3.5.2 PHOTOMICROGRAPH OF MONNEX DISCHARGED THROUGH THE POWDER DISSEMINATOR, MAGNIFICATION = 360X

runs 7, 9, and 10 were extremely encouraging. In fact, it appeared that products from the rocket motor were sufficient to extinguish a cascade fire without additional agent. Subsequent efforts to extinguish pool fires, runs 14 through 26, concentrated on obvious differences between the pool and cascade fires. First, the successful cascade fire extinguishments required ground fire control with AFFF to eliminate piloted reflash. With pool fires, the rocket blast blew some burning JP4 out of the pan and reflash sometimes appeared to originate in this displaced fuel. Two procedures were employed to minimize this source of reignition; (1) the fuel pan was filled with rocks to reduce the splash and (2) just before the test, AFFF foam was applied around the downwind side of the pan to extinguish fuel blown out of the pan. Second, the trejectory of the powder through the cascade screen provides an initial contact at the base of the combustion zone. With a pool fire and a nearly horizontal powder trajectory, most of the powder passes through the combustion zone well above the fuel pyrolysis region. Rocket orientation 5 in Table 3.1 provided a downward trajectory to force more powder into the interface between fuel and combustion zone. Third, the burning rate for pool fires was normally somewhat greater than for cascade fires; therefore, the ratio of powder concentration to concentration of reactive species in the combustion zone is more favorable for extinguishment in the cascade fires. Two procedures were employed to increase the powder to species ratio for pool fires. In runs 18 through 26, the powder concentration remained essentially constant while the burning rate and thus the species concentration was reduced by limiting the exposed fuel area either with rocks or foam. In runs 25 and 26 two disseminators were discharged simultaneously thereby doubling the powder concentration. In all cases except hand extinguishment tests 18 and 19, these measures were insufficient to achieve extinguishment with a pool fire. Repeatedly the powder appeared to eliminate flames over the fuel bed but a reflash always occurred. Reignition requires either a hot surface or a residual flame; however, obscuration by the remaining powder prevented an indentification. Since the pool fires were easily extinguished with AFFF, the remaining effort was concentrated on cascade fires.

In view of the easy extinguishments achieved in tests, 7, 9, and 10, the results from cascade fire tests 27 through 36 were very surprising. Intially, these tests were designed to establish the extinguishment capacity of single and multiple disseminator units; however, the goal degenerated into an unsuccessful effort to repeat the extinguishments of tests 7, 9, and 10. Only one cascade fire was successfully extinguished at Site 300 and that was

in test 32, where the fuel flow had been reduced to 3.8 gpm, i.e., 58 percent of the normal flow.

A similar reduction in fuel consumption with the 20 ft cascade fire, in test 31, i.e., 9 gpm or 68 percent of the nominal test value, did not result in successful suppression. Visually the flame characteristics at Camp Parks and Site 300 appeared the same; however, quantitative information about temperatures and the combustion rate per unit volume are not available.

3.3.2 Agent Applications

The four application parameters of interest are; (1) type of powder, (2) application concentration, (3) application pattern, and (4) residence time for the powder in the combustion zone. Due to the low number of successful extinguishments, the relative efficiencies of Monnex and PKP could not be established from these tests. Table 3.1 shows comparable performance for both agents in the four successful extinguishments where a comparison was possible, i.e., disseminator test 7 and 9 and hand extinguisher tests 18 and 19. In some of the failures, there was a visual impression that Monnex was slightly more effective than PKP but no objective data were attained to establish this point.

Application concentrations and residence times were discussed in Section 3.2. Aside from the slight variation in discharge time, the principle change in concentration occurred when two disseminators were fired simultaneously at the same fire area, e.g., tests 25, 26, on pool fires and 32, 34, and 35 on cascade fires. Doubling the concentration did not extinguish the fires except in test 32 where the burning rate was simultaneously reduced; therefore, the difference between Camp Parks and Site 300 does not appear to be a proximity to the critical application density that was exceeded in a few tests but not in others. Similarly, the extinguishment in test 10 indicates that under the proper circumstances, a very short residence time and small concentration can be adequate. If type, amount and residence time are eliminated, the only remaining application variable is the pattern or distribution of the powder. Several factors influence the pattern and completeness of coverage as the powder passes through the flames, e.g., nozzle size and orientation, aiming point, and ambient wind. In the successful extinguishments, the nozzles had been enlarged by erosion and the vertical cross section of the powder cloud was slightly larger than for the standard size nozzle. Obviously, the double disseminator firings could overcome this small factor but the pattern distribution is probably not uniform throughout the cloud. For example, the films of shots 32, 34, and 35 show a

reflash starting at the same point on the cascade screen, therefore, a localized hot spot or protected flame remained to reestablish the fire. The powder trajectory is determined by the rocket aming point and the wind. In tests 29 through 36 the rockets were fired in line with the wind. Inadvertently the aiming points were well established in tests 29, 33, and 36 when misfires blew the end off the disseminator and punched holes through the screen. Besides confirming a well aimed charge, the holes shown in Figure 3.6 also indicate a hazard with this type of dissemenator.

In the hand extinguishment applications the pattern could be limited to the most critical region of the fire and in two pool fires with the reduced burning rate, i.e., 18 and 19, the pattern and longer exposure time successfully extinquished fires that were never suppressed by the disseminator. On the other hand, none of the cascade fires were extinguished with hand extinguishers. However it should be noted that these tests were made without the use of AFFF to control the ground fires.

3.3.3 Environment

The principal environmental factors were wind and substrate. Due to the small number of extinguishments achieved, no correlation can be drawn between the environment and suppression although it was obvious that both of these environmental factors influenced the fire characteristics. For example, the wind blown cascade fire described in Section 2.3.1 and shown in Figure 2.9 appeared hotter and combustion was more complete than for a corresponding fire in the still air. Since the successful extinguishments and most of the failures occurred under comparable ambient winds, this factor does not appear to be controlling suppression.

The substrate was used to modify the burning rate in tests 18 through 25. With the hand extinguisher, it was obviously easier to suppress the slower burning pool fires. Although not demonstrated, a corresponding behavior with any disseminator was assumed in the design of tests 22 through 25. In the hand held extinguisher tests 18 and 19 some persistent pockets of flame were powdered repeatedly before final extinguishment was achieved. The rocket powdered disseminator did not afford this flexibility.

4.0 CONCLUSIONS

The disseminator is capable of rapidly discharging powder agent, however, the system was not particularly effective in extinguishing either cascading or pool fires of JP4. In most of the tests, the flames were momentarily

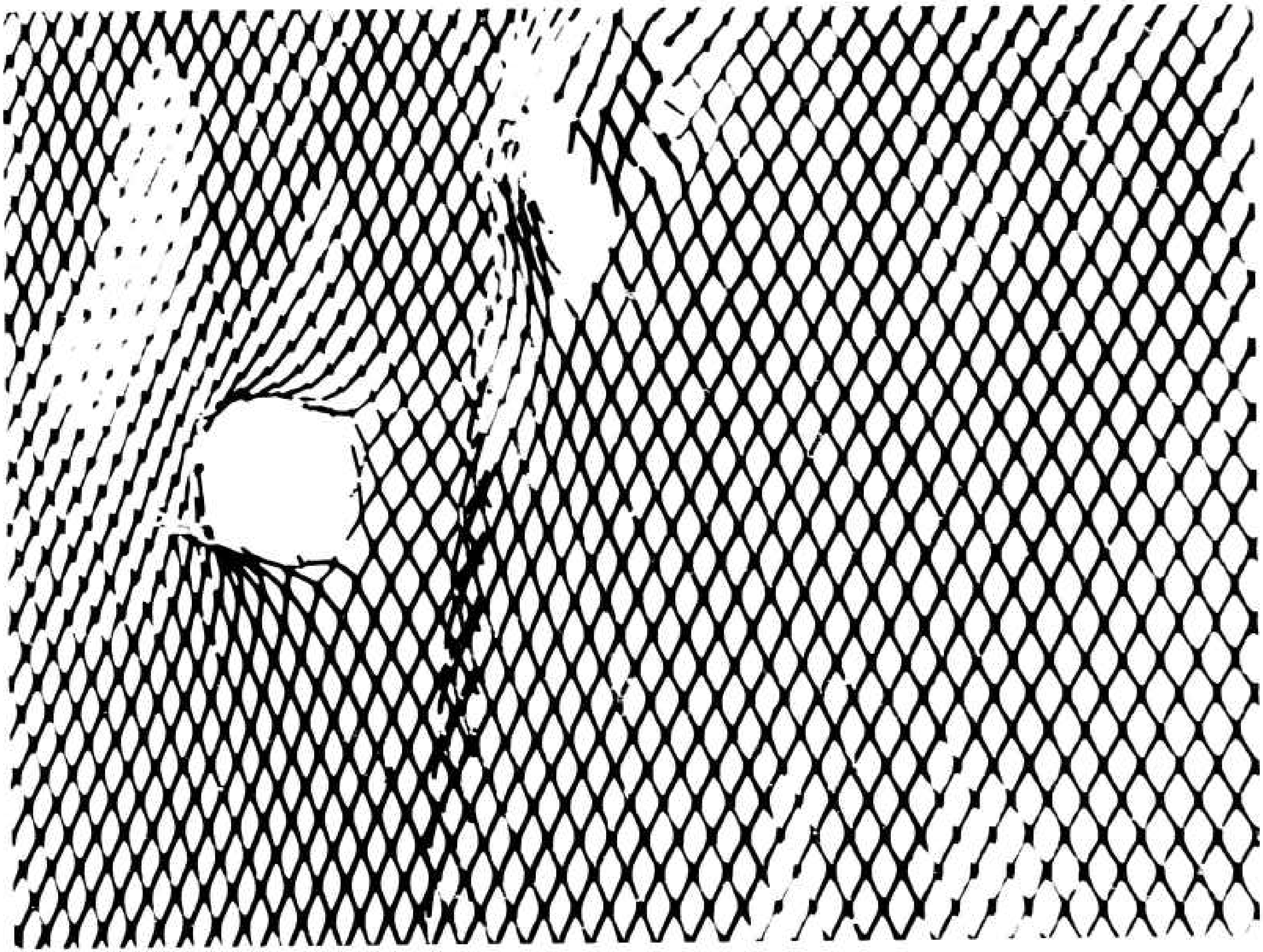


FIG. 3.6 HOLES PUNCHED IN THE CASCADE FIRE SCREEN WHEN SAFETY BOLTS RELEASED THE EJECTOR HOUSING DURING AN OVERPRESSURE

suppressed as the powder passed through the combustion zone but either the residence time was too short or the coverage was too incomplete to prevent reflash. The extinguishment of ground fires with AFFF was always necessary to prevent a reflash of the cascade fire.

Theoretically, prompt simultaneous coverage of the entire combustion region appears to be advantageous but some of the side effects inherent in the high energies required for rapid dissemination appear to nullify the advantage of speed. For example, low-cloud density and short-residence time are conducive to reflash. Also the high velocities complicate practical development because targets would have to be selected carefully to avoid complications with the 150 mph blast.

The lack of reproducibility indicates a deficiency in our understanding of cascade fires and the parameters that must be controlled or measured in order to achieve consistent results. Although the same ritual was followed at Camp Parks and Site 300, the disparity in results demonstrated the lack of information about some important variable. A reliable method of characterizing the test fire is needed to eliminate this source of uncertainty.

5.0 APPENDIX

5.1 Compositions of Propellant Grain and Ignitor

5.1.1 PBAN-175 Propellant

Potassium Perchlorate unground	56.1%
ground to 11 μ	22.1%
Thermax Carbon	1.98%
Dicotyladipate	2.86%
PBAN Monomer	12.96%
Methyl Nadic Anhydride	.7%
DER-332 Epoxy	3.48%

5.1.2 Ignitor

Magnesium, Teflon Pellets	9 gram
Boron	6 gram
S94 Dupont Squib	

Mag-Teflon Pellets	
Magnesium 18 ± 5 μ	60%
Teflon No. 5	40%

5.2 Slurry Feed System

5.2.1 Experimental Densities of Various Monnex Slurries

Liquid Carrier	% Monnex	Slurry Density, gm/cc
Carbon Tetrachloride	46	1.68
Trichlorethylene	51	1.56
Water	71	0.989

All slurries were made in a Waring blender that produced noncastable, plastic slurries which could be moved about with gentle pressure from a spatula. However, both organic slurries hardened considerably with two weeks aging. For this reason and the fact that the water slurry gave a higher loading of Monnex, it was decided to go with a 70 percent Monnex in water slurry for initial experiments.

5.2.2 Slurry Feed Rate

A pressure drop vs slurry flow rate curve was determined experimentally in the laboratory using the actual slurry distribution plate with a slot depth equal to 0.054 in., i.e., Figure 5.1. Lacking data for the friction loss down the delivery tube, the actual injector pressure drop was estimated to be 650 psi; consequently, the extrapolated curve would predict a flow rate of 26 lb/sec.

In a burning time of 0.8 sec the predicted slurry disseminated should be 20.8 lb. In the single disseminator test about 1/5 of the agent was not discharged. On the basis of visual observations it is believed that the slurry made in the 5-gallon mixer did not have the same flow characteristics as the slurry made in the Waring blender. This fact, combined with the guess at the injector pressure drop, is advanced as the primary reason for not disseminating all of the slurry.

5.2.3 Design Calculations for Slurry Dissemination

$$C^* = \frac{A_t P_c g}{\rho r_b A_p} = 4004 \text{ ft/sec}$$

where C^* = experimentally determined characteristic exhaust

$$\text{velocity} = \frac{I_s g}{C_F}$$

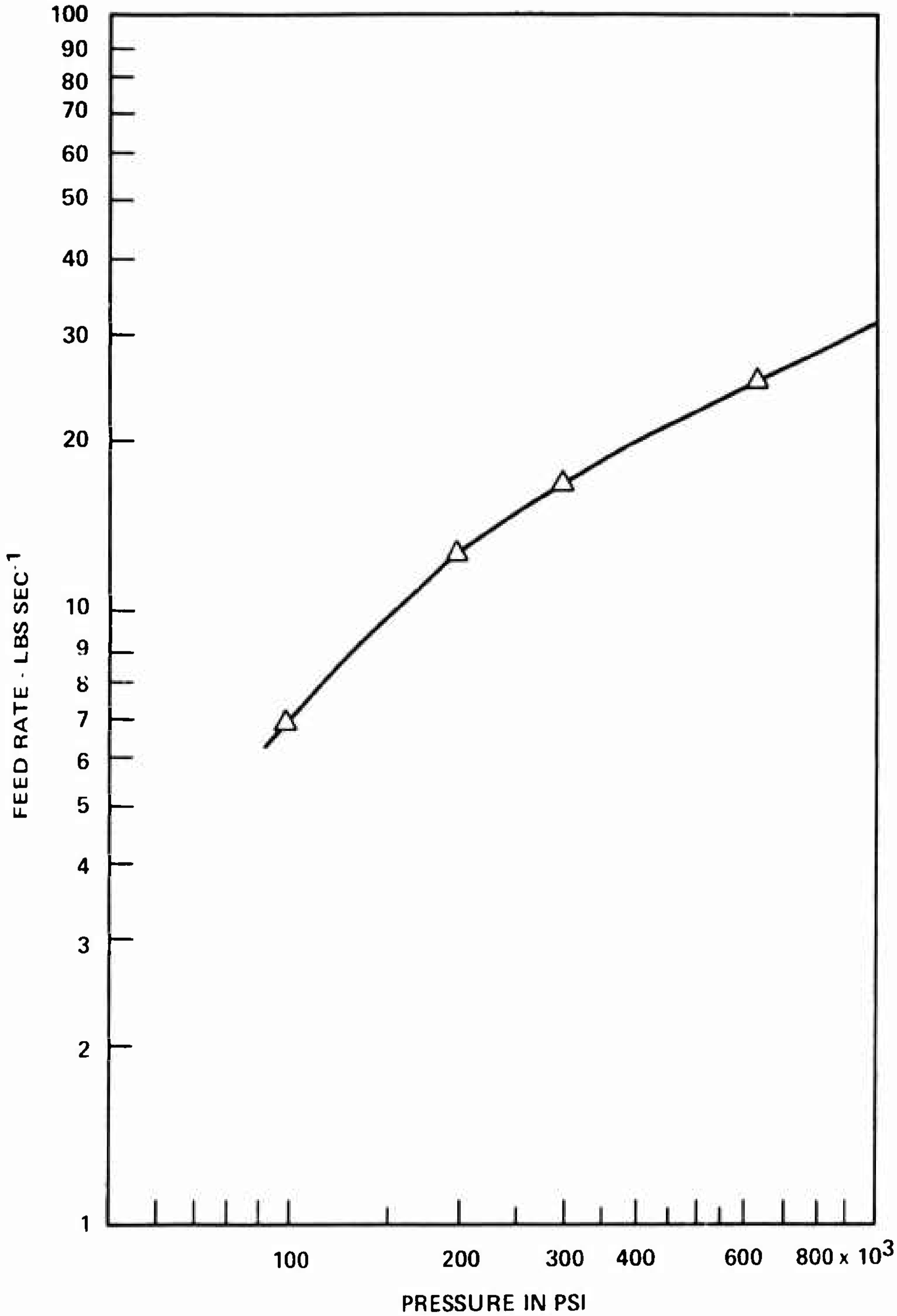


FIG. 5.1 SLURRY FEED RATE THROUGH INJECTOR SLOTS AS A FUNCTION OF INJECTION PRESSURE

I_s = specific impulse

g = gravity, ft/sec^2

C_F = thrust coefficient

A_t = nozzle throat area, in^2

P_c = chamber pressure, lb/in^2

ρ = propellant density, lb/in^3

r_b = propellant burning rate, in/sec

A_p = propellant burning surface area, in^2

The nozzle throat area becomes:

$$A_t = \frac{(4004)\ (.0691)\ (1.25)72.2}{(1265)\ 32.2} = 0.614 \text{ in}^2$$

For two nozzles

$$A_t = 0.307 \text{ in}^2 \text{ each}$$

$$d_t = \frac{4A_t}{\pi} = \frac{4(.307)}{\pi} = 0.625 \text{ in.}$$

approximate burning time for 1 in. web thickness;

$$t_b = \frac{1 \text{ in.}}{1.25 \text{ in/sec}} = 0.8 \text{ sec}$$

For the nozzle exit diameter:

$$\frac{P_c}{P_e} = \frac{1265}{15} = 84$$

From Sutton, page. 62 for the above pressure ratio

$$\frac{A_x}{A_t} = 8.5$$

$$A_{exit} = 8.5 \times 0.307 = 2.61 \text{ in}^2$$

$$A_x = \frac{\pi d_x^2}{4}$$

$$d_x = \frac{4(2.61)}{\pi} = 3.32 = 1.77 \text{ in.}$$

since the available space was 1.5 inches an expansion to atmospheric pressure was impossible, consequently, the exhaust velocity was less than Mach 3.

$$A_x = \frac{\Pi(1.5)^2}{4} = 1.766$$

$$\frac{A_x}{A_t} = \frac{1.766}{.307} = 5.75$$

$\frac{P_c}{P_e} = 47$, from which Sutton gives a velocity ratio

of $\frac{V_x}{V_t} = 2.1$ gas mach no. at exit

5.3 Powder Fluidization and Dissemination Systems

Initially it was planned to design the slurry and powder dissemination with as much compatible hardware as possible.

5.3.1 Position of Gas between Nozzles & Agent Reservoir:

The intention was to use 1/3 of the gas for fluidization and 2/3 for nozzle flow. This assumption is checked by calculating the contribution of the propellant burning to each set of nozzles.

For two main nozzles. 0.51 in. in diameter

$$A_p = \frac{A_t P_c g}{C^* \rho r_b}$$

$$= \frac{2 \times \Pi(.510)^2}{4} \; \frac{(1250)\ 32.2}{(4004)\ (.0691)\ 1.25}$$

$$= 47.5 \text{ in}^2$$

$$\frac{\text{Ap to main nozzle gases}}{\text{AP total}} = \frac{47.5}{72.2} = 0.66$$

For three tank fluidization nozzles with d_t = 0.295

$$Ap = \frac{A_t P_c g}{C^* \rho r_b}$$

$$= \frac{3\Pi(.295)^2}{4} \frac{(1250)\ 32.2}{(4004)(.0691)\ 1.25}$$

$$= 23.85\ in^2$$

$$\frac{\text{Ap to tank fluidization}}{\text{Ap Total}} = \frac{23.85}{72.2} = .33$$

So the initial assumption holds that 2/3 of gases flowed through rocket nozzles and 1/3 through tank fluidization nozzles.

5.3.2 Agent Reservoir Pressure

An estimated tank pressure is arrived at as follows:

Assume a desired tank pressure of 215 psi

$$\text{Then } \frac{P_t}{P_e} = \frac{1250}{215} = 5.8$$

$$\text{From Sutton } \varepsilon = \frac{Ae}{At} = 1.5$$

$$\text{and At} = \frac{\Pi(.295)^2}{4} = .06819\ in^2$$

$$\text{therefore } A_e = 1.5\ (.06819) = 0.1023$$

$$d_e = \sqrt{\frac{4}{\Pi}\ (0.1023)} = 0.361\ in^2$$

With the assumption that the outlet injector pressure would be at atmospheric pressure, our assumption gives a pressure drop across the dissemination tube of 215 psi.

Actually the injector pressure was in the range of 128 psig and the tank pressure was 530 psig for a total ΔP 400 psi across the tube carrying the powder from the fluidization tank to the tube outlet. In run 2 the powder discharged was in the range of 9 lbs. As a result of the unknown pressure drop being larger than our assumption, it was concluded that the tube friction and resulting pressure drop was the limiting flow condition. The delivery tube was made as large as the space between the nozzles would permit. This design gave a total powder discharge of about 16 lbs compared to 9 lbs and was acceptable for the continuing experiments.

5.3.3 Estimated Gas Velocity and Density (Assuming no Powder)

From thermochemical calculations for propellants the chamber gas density is $\approx$ 1 lb/ft^3. Assuming isentropic expansion from rocket chamber to fluidization tank:

$$\left(\frac{P_c}{P_j}\right)^{k-1/k} = \left(\frac{V_j}{V_c}\right)^{k-1}$$

where k = specific heat ratio = 1.27
so for 1 ft^3 of gas:

$$\left(\frac{1250}{420}\right)^{\frac{1.27-1}{1.27}} = \left(\frac{V_j}{1}\right)^{1.27-1}$$

$$(2.98)^{.213} = V_j^{\ .27}$$

$V_j = 2.364\ \text{ft}^3$, so 1 lb of gas now has 2.364 ft^3

and $Pg = \dfrac{1}{2.364} = 0.423\ \dfrac{\text{lb}}{\text{ft}^3}$

Gas Velocity at tube inlet:

$$V_i = \frac{\text{total cu. ft of gas}}{T_b\ A\ \text{tube}}$$

Total cu. ft of gas at inlet $= \dfrac{5\ \text{lb}}{.423\ \text{lb}} = 11.82\ \text{ft}^3$

$$A_{Tube} = \pi\left(\frac{\frac{1.380}{12}}{4}\right)^2 = \frac{\Pi(.115)^2}{4} = .01038 \text{ ft.}^2 \text{ and}$$

$$V_2 \cong \frac{11.82}{0.8 \times .01038} = 1423 \frac{\text{ft}}{\text{sec}}$$

Since this is above Mach 1, i.e., an impossible condition, it is concluded that the gas velocity is very close to mach 1 in the tube. This velocity limits the output of this particular design. An exact calculation of sonic velocity for this fluidized powder requires temperature data that is not available.

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